Development of STATCOM based PI and Fuzzy Voltage Controller for Self-Excited Induction Generator

A thesis

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CERTIFICATE

This is to certify that the thesis entitled "**Development of STATCOM based PI and Fuzzy Voltage Controller for Self-Excited Induction Generator**" being submitted by **Sumit Singh (710EE2127)**, for the award of the degree of **Bachelor of Technology and Master of Technology (Dual Degree)** in Electrical Engineering, is a bona fide research work carried out by him in the Department of Electrical Engineering, National Institute of Technology, Rourkela under my supervision and guidance

The research reports and the results embodied in this thesis have not been submitted in parts or full to any other University or Institute for award of any other degree.

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Abstract

With growing demand of electrical energy and limited availability of fossil fuels has led to the use of non-conventional sources (like Wind, Solar, Tidal etc.) which are abundant in nature and pollutant free. The brushless generation using Induction generator with excitation capacitor known as self-excited induction generators driven by constant speed prime movers are becoming more popular because of its low cost, ruggedness, low maintenance and no need of DC excitation system since last two decades. Moreover, these generators can also be operate as stand-alone system to provide electricity to isolated rural areas where transmission of power through grid is difficult and uneconomical. However the fundamental problem associated with such generation scheme are poor voltage regulation under varying load. In order to regulate its terminal voltage with varying load the active and reactive power levels at PCC (point of common coupling) have to be maintained constant.

The active and reactive power level are regulated by using modern power electronic converters. But survey shows that existing controllers are either difficult to implement or uneconomical or designed for particular load only. This thesis is intended to develop a STATCOM based voltage controller using PI controller for SEIG feeding both linear and non-linear loads driven by constant speed prime mover. The PI controller based voltage regulator has poor dynamic response hence a Fuzzy controller based voltage regulator using STATCOM is also developed. The advantages of using Fuzzy Controller over PI Controller for development of STACOM based voltage regulator for SEIG is investigated.

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List of Symbols

v_{qs}^{s}, v_{ds}^{s}	Stator q and d axis voltage in stationary reference frame
v_{qr}^{s}, v_{dr}^{s}	Rotor q and d axis voltage in stationary reference frame
i_{qs}^{s}, i_{ds}^{s}	Stator q and d axis current in stationary reference frame
i_{qr}^{s}, i_{dr}^{s}	Rotor q and d axis current in stationary reference frame
r_s	Stator resistance of induction machine
r_r	Rotor resistance of induction machine
ω_r	Speed of rotor
l_s	Inductance of stator of induction machine
l_r	Inductance of rotor of induction machine
M	Magnetizing inductance
T_e	Electromagnetic torque
T_{shaft}	Shaft torque
J	Moment of inertia of generator
i_m	Magnetizing current
C_{eq}, C_{ed}	Excitation capacitor values along q and d axis
R_L, L_L	Load resistance and inductance
V_m	Peak value of voltage
u_a, u_b, u_c	In-phase unit vectors
w_a, w_b, w_c	Quadrature unit vectors

i_{smq}^{*}	Peak quadrature supply current component along q axis
i_{smd}^{*}	Peak quadrature supply current component along d axis
$i_{saq}^{*}, i_{sbq}^{*}, i_{scq}^{*}$	Reference supply currents
$i_{sa}, i_{sb}, and\ i_{sc}$	Source currents
V_{pref}	Reference ac voltage
V_{dcref}	Reference ac voltage
V_{dc}	DC bus voltage
I_{sa}, I_{sb}, I_{sb}	SEIG line currents
$I_{Load\ abc}$	Three phase load current
V_{abc}	Three phase SEIG terminal voltage
I_{ma}, I_{mb}, I_{mc}	Three phase STATCOM currents or compensating currents
V_m	Magnitude of terminal voltage of SEIG

Chapter-1

Introduction

1.1 General

With increasing demand for electrical power, more emphasis is given on the renewable source of energy for producing electrical power. The depletion of conventional fuels has led to the use of renewable sources of energy like solar, wind, biomass, tidal, etc. Of these, the wind energy is found to be most suitable, clean, abundant and economical form of the non-conventional sources.

Earlier Synchronous generators are used for power generation using wind energy. But their application is limited as they cannot produce electricity at variable speed, require separate DC excitation system and require more maintenance. But now the brushless generation using Induction generator are more commonly used. The induction generator can be used either in grid connected mode or in standalone mode as self-excited induction generators [2]-[10]. The operation of induction generator as standalone system is gaining more attention, as they can provide power to remote areas where it is difficult or uneconomical for power transmission line to supply power. Thus the advantage of using induction generator are low cost, ruggedness, low maintenance, simple operation, good dynamic response and no need of separate DC excitation system.

The SEIG are proved to be best candidate for generating electricity from wind because they don’t need external power supply for excitation and hence can be operate in remote areas [30]-[35]. The main problem with SEIG is poor voltage regulation under varying loading conditions. They demand variable reactive power for voltage regulation under different loading conditions [3]-[8]. This work mainly deals with the investigation on voltage controller for SEIG driven by constant prime movers. In order to maintain the SEIG terminal voltage constant, the necessary reactive power as demanded by the load must be provided, for this purpose various controllers are developed which can provide reactive power [18]-[27].

Thus in order to regulate the SEIG terminal voltage and frequency both active and reactive power level at point of common coupling must be maintained constant. With the development of solid state power electronics converters, various controllers like static var compensation (SVC), static compensator (STATCOM) controller, and generalized impedance controller (GIC) have been developed for SEIG [1]-[10]. This thesis aims to investigate the STATCOM based voltage regulator for SEIG which is driven by constant speed prime mover feeding both linear and non-linear loads for wind energy application. Thus for maintaining the SEIG terminal voltage constant, the necessary capacitive power demanded by the excitation system of the generators.

1.2 Literature survey

There are several research in the field of modelling, steady state performance and transient analysis of SEIG as an isolated power generation. Earlier induction machines are commonly used as motors and its application as a generator is very rare. However, the application of induction machine as a self-excited induction generator is first discovered by Basset and Potter et al. [1]. Basset proposed the process of voltage built up using induction machine with the help of capacitor self-excitation. Induction machine can be operated as generator if sufficient amount of inductive VAR is given to machine, to provide machine excitation at particular speed. The dynamic model of SEIG is based on d-q reference frame models based on machine model developed by Krause [11]. Novotny et al. [12] developed a model for induction generator in synchronously rotating d-q reference frame under steady state operation. The only demerit with this model is that this can be used under steady state analysis only, not for transient analysis. Bahrain et al. [13] described that there is minimum and maximum value of capacitor with in which the machine will excite at no load for particular speed. Also it shows that there is a critical value of load impedance below which machine will not excite for any value of capacitor. Wang et al. [14] represented the dynamic d-q model of SEIG which shows that with variation in loads the generator voltage varies, but it does not show any relation regarding the dynamic speed of rotor when generator is loaded. The effect of magnetizing inductance on self-excitation is discovered by Seyomut et al. [15] and the loading analysis of an isolated induction generator is also presented and discusses how the operating frequency and generated voltage are affected by taking only resistive load.

The self-excited induction generator has major demerit i.e. they suffer from poor voltage and frequency regulation with variation in load and varying the speed of prime mover. Many researchers have proposed various method for maintaining the voltage and frequency of SEIG constant for standalone application. By the using static VAR compensators (SVC) the smooth operation of SEIG can be achieved as reported by Brennen et al. [16], but this controller requires capacitors and inductors of very large sizes and it also inject harmonic in the SEIG system. Later Electronic Load Controllers (ELCs) [17]-[20] have been proposed for self-excited induction generator for constant power prime movers applications like wind turbines, micro hydro turbines etc., the magnitude and frequency of the generated voltage are maintained constant with varying load conditions. As the SEIG is connected to prime mover, the input power and speed are not constant because of variation in prime mover speed and variable consumer load which in turn changes the magnitude of generated voltage and frequency. For maintaining the voltage constant, a shunt connected Voltage Source Inverter (VSI) [21] is proposed with an energy storage unit on the dc side, typically a battery bank is used for absorbing or compensating the active and reactive power as demanded by SEIG and load. Perumal et al. [22] integrated the generalized impedance controller with SEIG to maintain voltage and frequency, which operates on the principle of PWM (pulse width modulation) based voltage-source-inverter which uses a dc link battery on dc side. It is capable of providing both bi-directional control of active and reactive power. This controller has fast dynamic response but it developed for static load only, the dynamic and non-linear loads are not considered. Later a direct voltage control (DVC) method using PI regulator with lead-lag corrector and a feed-forward compensator is proposed by Geng et al. [23]. PI regulator is used for removing steady-state errors. The lead-lag corrector is used to enlarge the phase stability margin of the dominant poles whereas the feed-forward compensator is used to eliminate the harmonics present in the system. Kaseem et al. [36] described that a static reactive power compensator can be used for maintaining the terminal voltage constant of induction generator irrespective of load variation. The rotor speed and thereby the frequency are controlled using blade pitch-angle control. Deraz et al. [37] proposed an electronic load controller with a current controlled voltage source inverter (CC-VSI) which is connected in parallel with load to the AC terminals of induction generator. It implements three Fuzzy controller, one conventional PI controller and one hysteresis current controller for extracting the maximum available energy from the wind turbine as well as to maintain the generator terminal voltage constant with variation in speed of wind and main load. The whole system becomes complex because of the use of four controllers which is the major demerit of this regulator. A static synchronous series compensator (SSSC) and static compensator (STATCOM) is proposed by Singh et al. [38] to feed static and dynamic load. These controllers are not designed for non-linear loads, also the dynamic response of controller is very poor.

This thesis proposed the analysis and development of STATCOM based voltage controller for SEIG feeding driven by constant speed prime movers feeding linear and non-linear loads. The STATCOM consist of current controlled voltage source inverter (CC-VSC) and two conventional PI controller. This controller provide voltage regulation for both balanced or unbalanced load and linear or non-linear loads. Instead of PI controller, a STATCOM with fuzzy logic is also designed which provide better dynamic response, good voltage regulation and easy to implement as compared to conventional PI controllers.

1.3 Motivation and Objective

The standalone operation of induction machines as self-excited induction generator is gaining more popularity for supplying power to the remote areas where the transmission of power by grid is difficult to reach and involve high cost. Over past years extensive study has been carried out on analysis of SEIG and stated as follows.

a. The steady state performance analysis of SEIG
b. The selection of excitation capacitors
c. Use of SEIG as standalone system

SEIG has advantage of operating either in grid connected mode or standalone mode but it suffers from poor voltage regulation under variable loading conditions [1] –[12]. Different techniques have been developed for improving voltage regulation such as following

a. Switched capacitor scheme
b. Electronic load controller
c. Variable VAR controllers
d. Static synchronous series compensators etc.

These are reported in [15]-[27], which significantly improves the performance of SEIG, but the control circuit involve are either complex or difficult to implement or have very high cost. Some of the controllers are either designed for linear loads or non-linear loads but not both. Also the dynamic response of the controller involve is poor. Thus it motivates to first develop the dynamic model of standalone SEIG which is driven by constant speed prime mover and to design a reliable controller for regulating the voltage under different conditions.

Thus objective of this thesis are

a. To design a dynamic model of SEIG driven by constant prime mover
b. To investigate voltage build up process under different conditions
c. To model a STATCOM based controller with conventional PI control for regulating voltage
d. To develop a STATCOM based controller with Fuzzy logic for regulating voltage
e. To discuss the merits of using Fuzzy controller over conventional PI controller

1.4 Thesis Layout

The content of this thesis has been divided into following chapters:

Chapter-1: This chapter gives introduction about self-excited induction generator and problem of voltage regulation of SEIG. It also discusses about various controller which are designed for SEIG and their merits and demerits. It also present the literature review on isolated power generation employing induction generators. Various aspects of self-excited induction generator are discussed along with their controllers to regulate the voltage. Then the objective of the proposed work is presented in brief.

Chapter-2: This chapter present the MATLAB based modelling of detailed dynamic model of SEIG driven by constant prime mover. It also present the voltage build up process of SEIG under different condition. The effect of magnetic saturation on the performance of SEIG is also discussed.

Chapter-3: This chapter present the detailed analysis and development of STATCOM based voltage controller for self-excited induction driven by constant speed prime mover using conventional PI method in MATLAB/SIMULINK environment. The analysis and development of STATCOM based regulator, which is based on three leg voltage source converter (VSC), is investigated for self-excited for both balanced/unbalanced linear and non-linear loads.

Chapter-4: This chapter deals with design, analysis and development of STATCOM based regulator using fuzzy logic controller. The merits of fuzzy logic over conventional PI controller is also discussed.

Chapter-5: This chapter present the important aspects of STATCCOM based controller and bring out the main conclusion of the work. It also entitles the scope of future work on this area.

Chapter-2

DESIGN OF DYNAMIC MODEL OF SELF-EXCITED INDUCTION GENERATOR DRIVEN BY CONSTANT SPEED PRIME MOVER

2.1 General

The SEIG are proved to be best candidate for generating electricity from wind energy because they do not need external power supply for excitation and hence they can be operate in remote areas as standalone systems [29]-[35]. The concept of using induction machine as self-excited induction generator is discovered by Basset and potter et al. [1]. Induction machine can act as a generator if sufficient amount of variable inductive VAR is available necessary to provide machine excitation at particular speed. The dynamic model of induction machine based on d-q reference frame models based on machine model developed by Krauss [11]. Novotny et al. [12] developed a model for induction generator in synchronously rotating d-q reference frame d-q reference frame under steady state operation but this model can be used for steady state analysis only. Finally, Wang et al. [14] design the d-q model of SEIG which shows that dynamic generated voltage varies with applied load.

2.2 Modelling of SEIG

The dynamic model of SEIG is developed using stationary q-d reference frame considering both main and cross flux saturation. The schematic diagram of SEIG is illustrated in Fig. 2.1 with capacitor bank, load and prime mover. The schematic q-d diagram of three phase SEIG along with balanced three phase excitation and load connected across its terminal is shown in Fig. 2.2. For development of self-excited induction generator model, the q-d arbitrary reference frame model of the machine is transformed into stationary reference frame model.

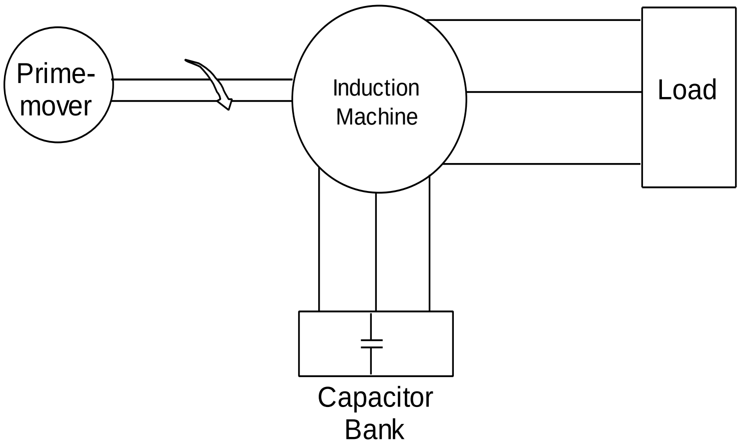


Fig. 2.1 Schematic diagram of SEIG

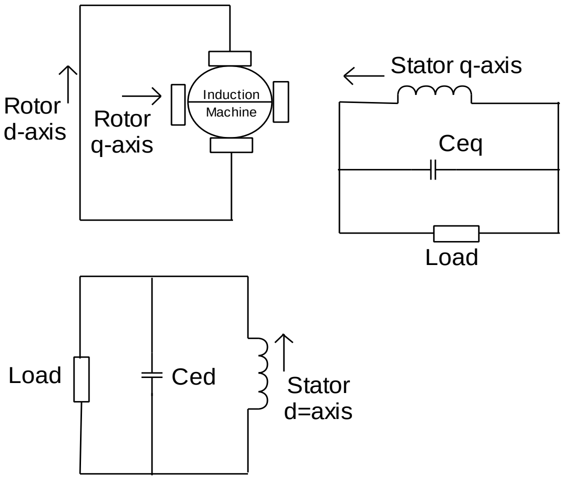


Fig. 2.2 q-d axis diagram of SEIG

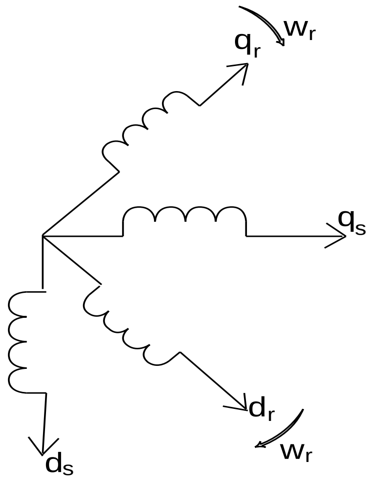


Fig. 2.3 Equivalent two phase machine

For the two phase machine as shown in Fig. 2.3, we need to represent both stator and rotor variables in stationary reference frame. The stator equation in stationary reference frame is represented as

$$v_{qs}^{s} = R_s i_{qs}^{s} + \frac{d}{dt}\varphi_{qs}^{s} \tag{1}$$

$$v_{ds}^{s} = R_s i_{ds}^{s} + \frac{d}{dt}\varphi_{ds}^{s} \tag{2}$$

The rotor equation in stationary equation are

$$v_{qr}^{s} = R_r i_{qr}^{s} + \frac{d}{dt}\varphi_{qr}^{s} - \omega_r \varphi_{dr}^{s} \tag{3}$$

$$v_{dr}^{s} = R_r i_{dr}^{s} + \frac{d}{dt}\varphi_{dr}^{s} + \omega_r \varphi_{qr}^{s} \quad (4)$$

The equation given above are of general induction machine. The steady state model of self-excited induction machine is illustrated in Fig. 2.4. The initiation of voltage build process and its sustenance depends on several parameters, such as load, the capacitance value, the residual flux and speed. Thus for self-excitation of SEIG, a capacitor bank of suitable value must be connected across the machine terminals, the core of machine must retain some amount of residual flux. The capacitor is used to provide necessary reactive power, which can produce magnetizing flux necessary for developing the voltage. But self-excited induction generator shows variation in its terminal voltage with variation in load.

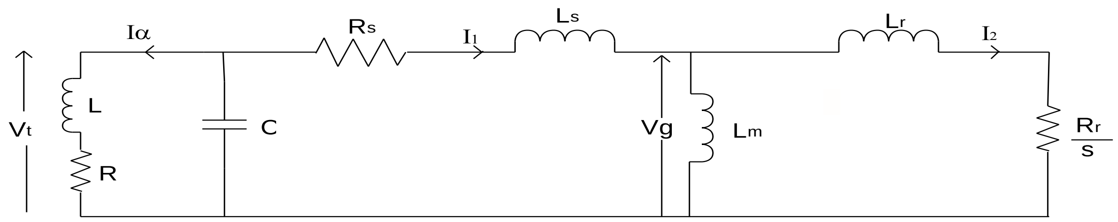
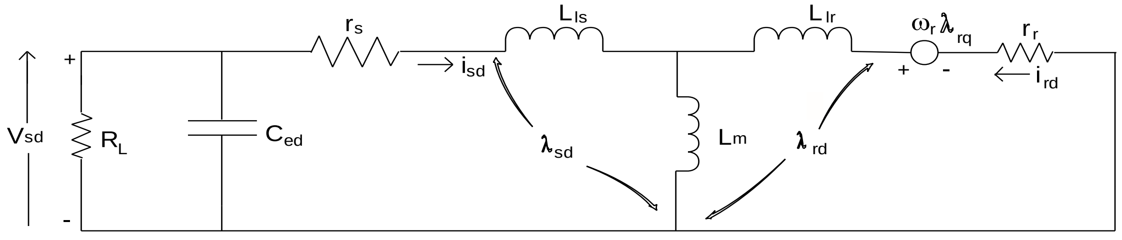


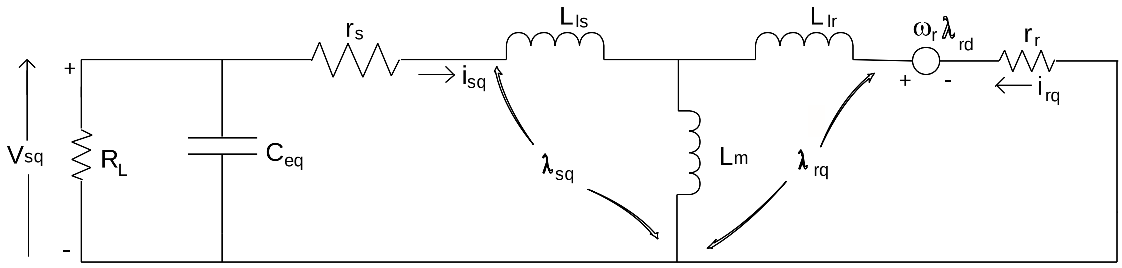
Fig. 2.4 Steady-state circuit model of self-excited induction generator

The magnetizing reactance of machine does not remain constant, but varies with circuit parameters and speed, it decreases with increasing saturation. There is minimum value of capacitance for any given value of load, below which the self-excitation process does not occur at any speed. This critical value decreases with increase in load. Also, there is minimum excitation speed and maximum load value beyond which self-excitation process cannot sustain with any value of capacitance. Furthermore, there is critical value of speed below which machine will never develop voltage irrespective of any combination of load and capacitance.

The equivalent q-d circuit of SEIG is illustrated in Fig. 2.5, the directions of referenced currents and voltages are also indicated in this figure.



2.5(a): d-axis reference frame



2.5(b): q-axis reference frame

Fig. 2.5 Dynamic d-q model of SEIG in Stationary reference frame

Applying KVL in q-d model of SEIG, we get following equations

$$V_{sd} = (r_s + pL_{ls})i_{sd} + pL_m(i_{sd} + i_{rd}) \tag{5}$$

$$V_{sq} = (r_s + pL_{ls})i_{sq} + pL_m(i_{sq} + i_{rq}) \tag{6}$$

$$i_{rd}r_r + \omega_r\lambda_{rq} + p(L_m + L_{lr})i_{rd} + pL_m i_{sd} = 0 \tag{7}$$

$$i_{rq}r_r - \omega_r\lambda_{rd} + p(L_m + L_{lr})i_{rq} + pL_m i_{sq} = 0 \tag{8}$$

Where, $\lambda_{rd} = L_r i_{rd} + L_m i_{sd}$, $\lambda_{rq} = L_r i_{rq} + L_m i_{sq}$

$L_r = L_{lr} + L_m$, $L_s = L_{ls} + L_m$

Using q-d components of stator current (i_{sd} and i_{sq}) and rotor current (i_{rd} and i_{rq}) as state variables, the following differential equations 9-12 are derived

$$\frac{di_{sd}}{dt} = \frac{1}{L_rL_s - L_m^2}[L_r v_{sd} - L_r r_s i_{sd} + L_m r_r i_{rd} + L_m \omega_r L_r i_{rq} + \omega_r L_m^2 i_{sq}] \tag{9}$$

$$\frac{di_{sq}}{dt} = \frac{1}{L_rL_s - L_m^2}[L_r v_{sq} - L_r r_s i_{sq} + L_m r_r i_{rq} - L_m \omega_r L_r i_{rd} - \omega_r L_m^2 i_{sd}] \tag{10}$$

$$\frac{di_{rd}}{dt} = \frac{1}{L_rL_s - L_m^2}[-L_m v_{sd} - r_r L_s i_{rd} - \omega_r L_s L_r i_{rq} - \omega_r L_m L_s i_{sq} + L_{,m} r_s i_{sd}] \tag{11}$$

$$\frac{di_{rq}}{dt} = \frac{1}{L_rL_s - L_m^2}[-L_m v_{sq} - r_r L_s i_{rq} + \omega_r L_s L_r i_{rd} + \omega_r L_m L_s i_{sd} + L_{,m} r_s i_{sq}] \tag{12}$$

The electromagnetic torque can be calculated as follows

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right) L_m[i_{sq}i_{rd} - i_{sd}i_{rq}] \tag{13}$$

As we know that the magnetizing characteristic of SEIG is nonlinear. Thus the magnetizing inductance L_m is not a constant. The value of inductance (L_m) depends on the instantaneous value of magnetizing current i_m and given by $L_m = f(I_m)$. During simulation, the magnetizing inductance L_m is continuously updated according to function of magnetizing current in each step. The magnetizing current is given by

$$I_m = \sqrt{(i_{sd} + i_{rd})^2 + \left(i_{sq} + i_{rq}\right)^2} \tag{14}$$

With the magnetizing characteristics using fourth order polynomial, the magnetizing inductance L_m is calculated for the test machine. By applying curve fit technique to the relationship between L_m and i_m , the 5th order polynomial is obtained, by performing synchronous speed test on the test induction machine. The torque balanced equation is given by

$$T_{shaft} = T_e + J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} \tag{15}$$

2.2.1 Excitation Model

The excitation system introduces the following state equations (16) and (17) using d-q components of stator voltage (v_{sd} & v_{sq}) as state variables, from the circuit shown in Fig 5.

$$\frac{dv_{sq}}{dt} = \frac{i_{sq}}{C_{eq}} \tag{16}$$

$$\frac{dv_{sd}}{dt} = \frac{i_{sd}}{C_{eq}} \tag{17}$$

Where $C_{eq}$and C_{ed} are the excitation capacitor values along q and d axis respectively.

2.2.2 Load Modelling

The d and q axis current equations for the resistive balanced is given by following equations

$$i_{Rq} = \frac{v_{sq}}{R_L} \tag{18}$$

$$i_{Rd} = \frac{v_{sd}}{R_L} \tag{19}$$

The d and q axes current equations for the balanced R-L load are derived from Fig. 5, and given by equations 20 and 210

$$i_{Rq} = \frac{(v_{sq} - R_L i_{Rq})}{pL_L} \tag{20}$$

$$i_{Rd} = \frac{(v_{sd} - R_L i_{Rd})}{pL_L} \tag{21}$$

If the load is capacitive in nature, then the capacitor value will be added to the excitation capacitor value.

2.3 Voltage build-up process in SEIG

The induction machine can be operate in standalone mode, if excited by suitable value of capacitor. When static capacitor are connected in shunt across the stator terminals of induction machine, voltage will be induced at its terminals provided the machine is driven by prime mover. For successful excitation machine must sustain small value of residual flux. This residual flux in the core of machine induces a small alternating voltage in the stator, this voltage induced is applied to the capacitor which generates a lagging magnetizing current which flows in stator windings. If the capacitance is of proper value, the current that flow in stator winding will be large enough to further increase the flux value already existing in air gap. With increase of air gap flux, the stator terminal voltage further increase which result in increase in magnetizing current drawn by capacitor and hence air gap flux further increases. This process goes on until the terminal voltage of generator reaches its rated value. The steady state value of terminal voltage is determine by the capacitive reactance of the connected capacitance and the saturation curve of the machine. Fig. 2.6. Represents the voltage developed V_t as a function of I_m, which determine the steady state point of voltage build up.

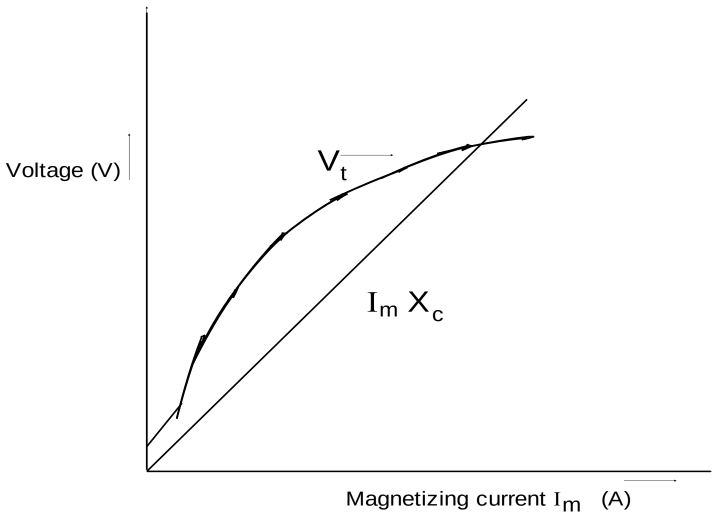


Fig. 2.6 Determination of Stable Operation of SEIG

2.4 Simulation of SEIG driven by constant speed prime mover in MATLAB/SIMULINK

The SEIG's dynamic model is developed using equations (5)-(19) in MATLAB/SIMULINK environment. The process of self-excitation is based on residual magnetism present in the rotor circuit and voltage build is excited by reactive power supplied by the capacitor. After the voltage is reaches to a steady state value, load is connected to the SEIG. The specification of induction machine is taken from [29] and is given below.

Induction machine rating: - 3.7kW, 415V, 7.5A, 4-Pole and its parameters are as follows:

$r_s(\Omega)$	$r_r(\Omega)$	$X_{ls}(\Omega)$	$X_{ls}(\Omega)$	$L_m(\mathrm{H})$	$J\ (Kg\ m^2)$
7.34	5.64	6.7	6.7	0.5	0.16

The magnetizing characteristic equation and constants are:

$$L_m = b_0 + bI_m + b_2 I_m^2 + bI_m^3 + b_4 I_m^4 + b_5 I_m^5$$

Where b_0 = 1.043, b_1 = -0.853, b_2 = 0.713, b_3 = -0.304, b_4 = 0.0576, b_5 = -0.0038

The performance characteristics of SEIG under the following condition has been observed.

1. Voltage build-up process
2. Switching in of load
3. Loss of excitation due to heavy-load

The three phase voltages and currents are obtained by applying d-q to a-b-c transformation as follows:

$$\begin{bmatrix} w_a \\ w_b \\ w_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} w_{sq} \\ w_{sd} \end{bmatrix} \qquad (22)$$

Where, w_a , w_b and $w_c$are three phase voltage or current quantities and w_{sq} and w_{sd} are two phase voltage or current quantities. The value of peak voltage is calculated as:

$$V_m = \sqrt{\frac{2}{3}\left(v_{an}^2 + v_{bn}^2 + v_{cn}^2\right)} \qquad (23)$$

$$v_{an} = V_m \sin(\omega t),\; v_{bn} = V_m \sin\left(\omega t - \frac{2\Pi}{3}\right), v_{cn} = V_m \sin\left(\omega t + \frac{2\Pi}{3}\right)$$

A 61.6 µF capacitor is used for excitation in generator. The SEIG is driven at synchronous speed of speed of 157.07 rad/s. The developed SEIG model is simulated in MATALB by using the numerical integration technique Runge-kutta fourth order method. The step length should be as small as possible for getting accurate and precise result, here it is taken between $1e^{-6}$ to $5e^{-6}$. In case of the SEIG the dynamics of voltage build up and stabilization mainly depends on the variation of magnetization inductance of machine. From the synchronous speed test, the magnetizing inductance L_m is obtained as function of magnetizing current I_m. The initial values of input states of q-d model i.e.$i_{sd}, i_{sq},\; i_{rd}, i_{rq}$ are assumed to be zero. For the self-excitation the residual magnetism of the machine is taken as initial values of v_{sq} and v_{sd}. The Simulink model of SEIG is shown in Fig. 2.7(a). Fig. 2.7(b) shows the subsystem of d-q induction generator model. Fig. 2.7(c) shows the system of stator and rotor d-q axis current derivation equations. Fig. 2.7(d) show the subsystem of dq-abc conversion and Fig. 2.7(e) shows the excitation capacitance sub-system.

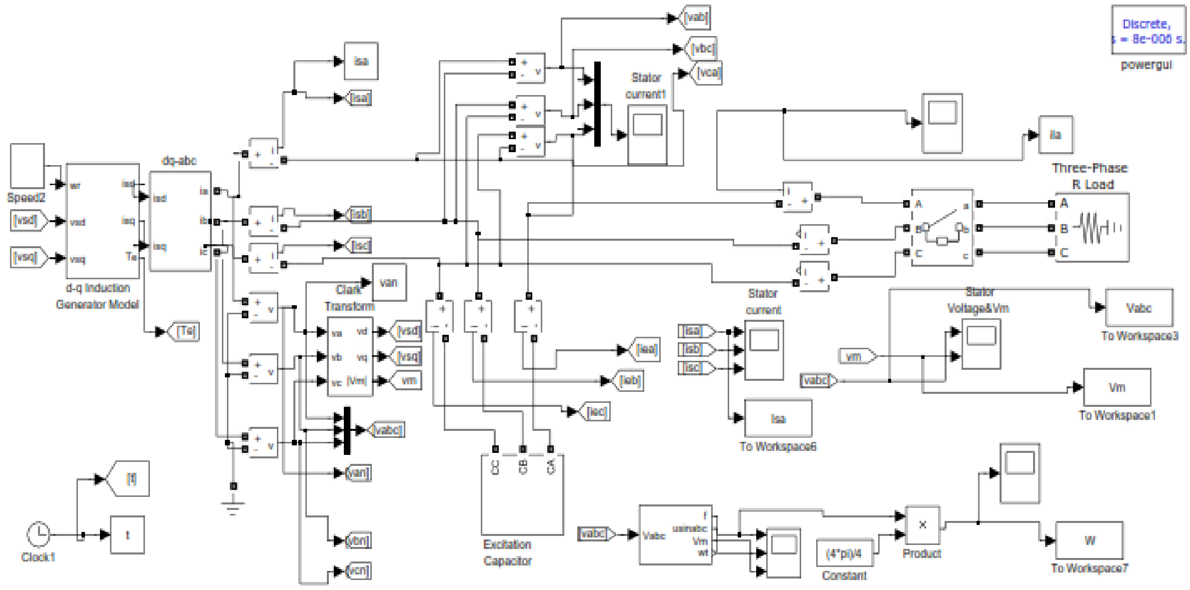


Fig. 2.7(a) Simulink model of SEIG in MATLAB

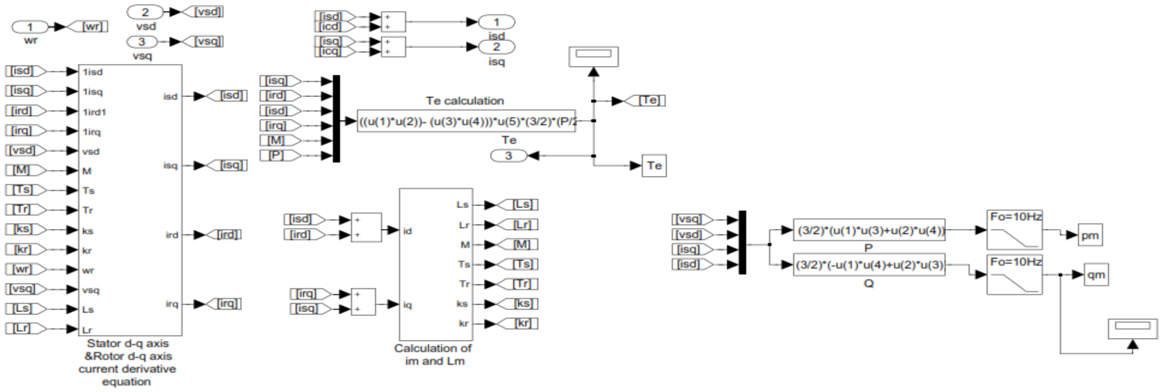


Fig. 2.7(b) Subsystem of d-q Induction generator model

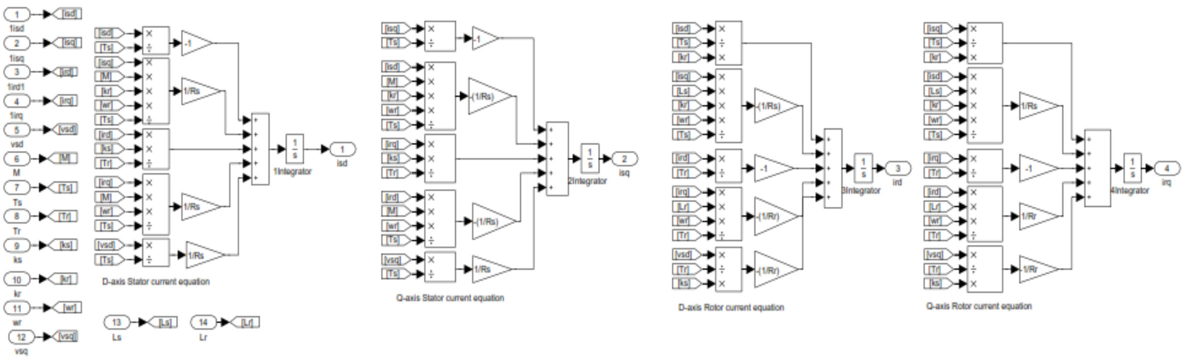
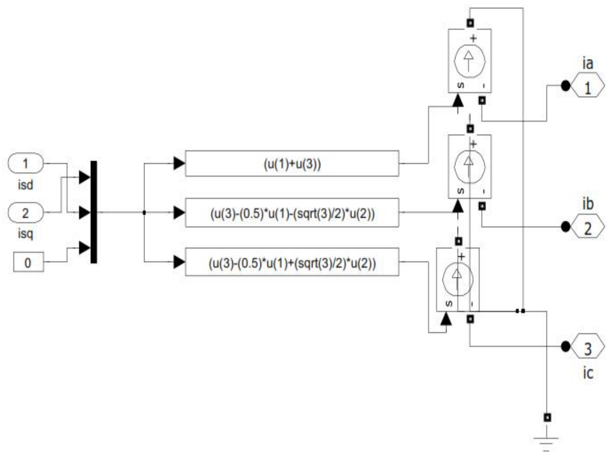


Fig. 2.7(c) subsystem of stator and rotor d-q axis current derivation



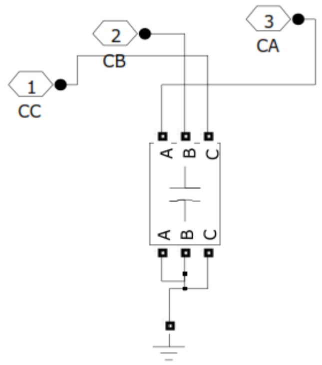


Fig. 2.7(d) d-q to abc conversion

Fig. 2.7(e) Subsystem of excitation capacitor

2.5 Results and Discussion

2.5.1 Self-excitation process

The generator is driven at synchronous speed of 157.07 rad/s and a three phase delta connected capacitor is bank of 61.6μF is switched in to its terminals. The residual magnetism taken in terms of v_{sq} andv_{sd} as 1 volt, which induces the voltage across self-exciting capacitors and thus producing magnetizing current in the stator resulting in higher voltage. This process goes on until the magnetic field reaches to its saturation. The simulation results of self-excitation process are shown in Fig. 2.8 (a)-(d). Fig. 2.8(a) shows the peak phase voltage of SEIG terminal, the SEIG steady state voltage peak voltage is 335 V (236 V RMS), which reaches steady state in 0.35 sec. Fig. 2.8 (b) shows the phase voltage of SEIG terminals. The steady state value of stator current at no load is 6.5 A and is shown in Fig. 2.8 (c) for phase a. Fig. 2.8 (d) shows the magnetizing current waveform and it attains its steady state value of 2.656 A at 3.5 sec.

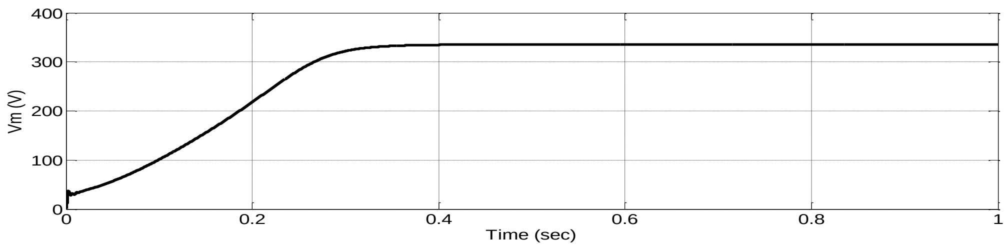


Fig. 2.8(a) Peak SEIG terminal voltage waveform

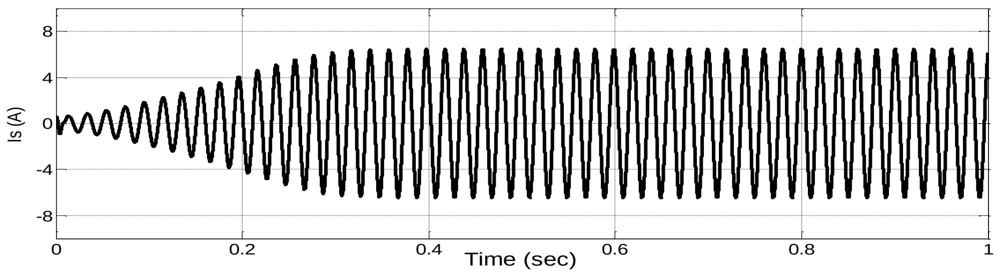


Fig. 2.8 (b) Phase ‘a’ current of SEIG at no load

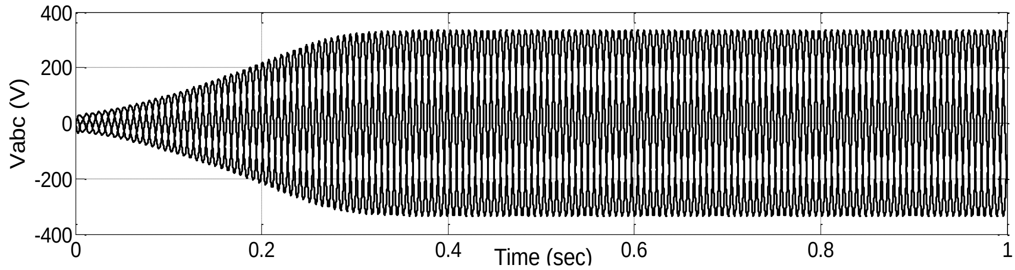


Fig. 2.8 (c) Waveform of SEIG terminal voltage (phase voltage)

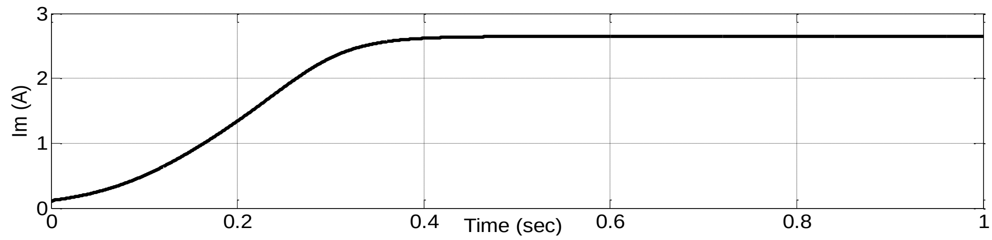


Fig. 2.8 (d) Magnetizing current waveform

2.5.2 Insertion of Load

Initially the SEIG is running at no load and steady state voltage and current are developed. Now at time t = 0.8 sec a balanced R-L load of 1 KW at 0.8 pf is suddenly connected to the SEIG terminals. It is observed that the steady state peak voltage at no load is 337 V, which reduces to 278 V when load is connected, as illustrated in Fig 2.9(a). Fig. 2.9(b) illustrates the phase voltage of SEIG with insertion of load. When generator is operating at no load, the load current is zero, but with load connection the current reaches a peak value of 1.1A and shown in Fig. 2.9(c). The stator current at steady state at no load is 6.5A, but it reduces to 4.75A when load is connected, shown in Fig. 2.9(d). With application of load the magnetizing current I_m decreases Fig. 2.9(e), which results in the reduced flux. With reduction in flux, the value of induced voltage also decreases.

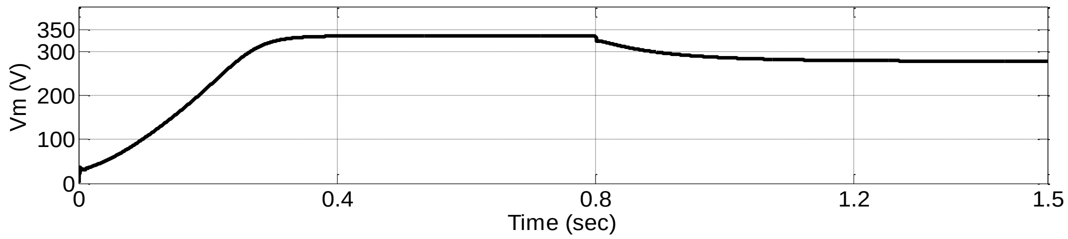


Fig. 2.9(a) SEIG peak voltage Waveform

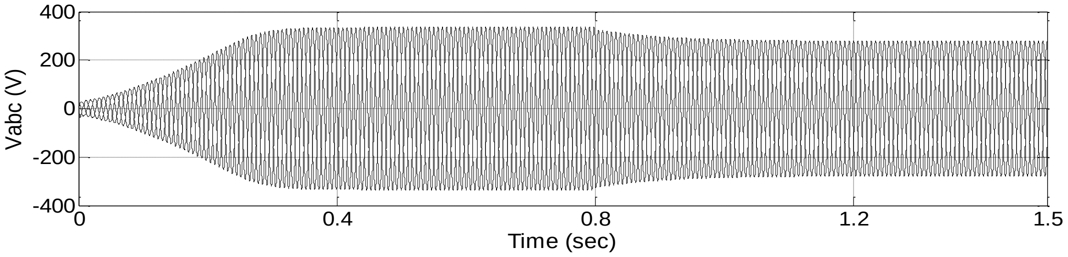


Fig. 2.9(b) Stator terminal phase voltage waveform

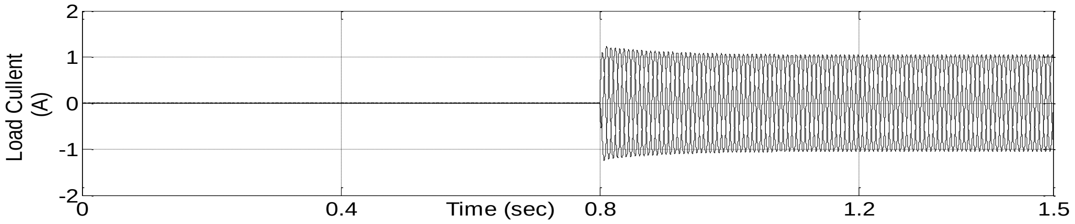


Fig. 2.9(c) Load current waveform

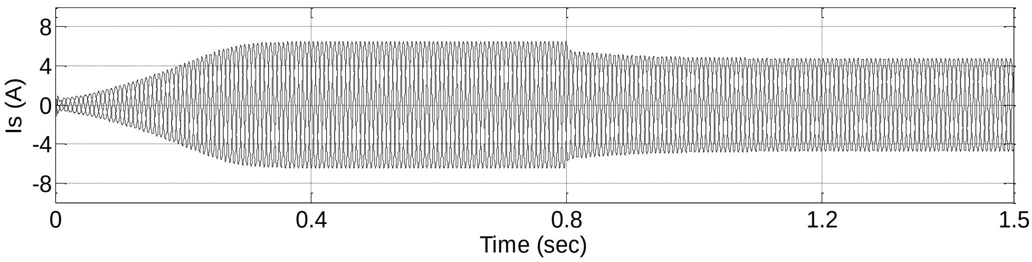


Fig. 2.9(d) Stator current Waveform

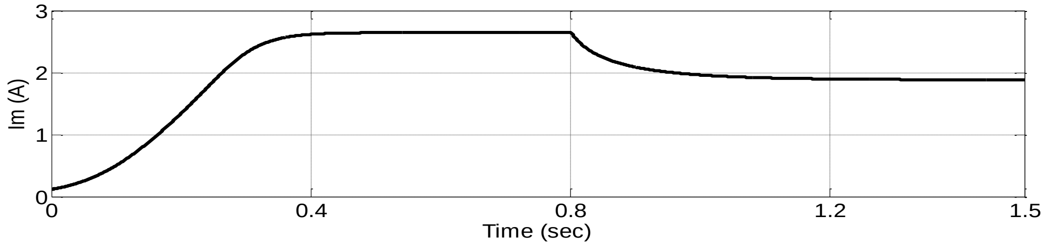


Fig. 2.9(e) Magnetizing current waveform

2.5.3 Loss of Excitation due to heavy-load

The SEIG which is initially operated under steady state condition having peak value of voltage 335 volts and R-L load of 0.5 KW is applied at t=0.8seonds having pf 0.8, voltage is reduced and reached a steady state voltage of 278 volt. At t=1.3 seconds an extra load is applied, of value 2.5KW R-L load, the SEIG line voltage collapse is a monotonous decay of the voltage nearly to zero shown in Fig. 2.10(a). Once the voltage collapse occurs, the re-excitation of the generator becomes difficult. Thus it shows the poor overloading capability of the SEIG. Therefore the load connected to the generator should never exceed beyond the maximum load the generator can deliver under steady state condition. But it may be mentioned here that the momentary excess stator current can operate protective relays to isolate the overload condition at the generator terminals to prevent voltage collapse. Fig. 2.10(b) shows the terminal voltage of SEIG. With increase in load, beyond its maximum value, the magnetizing current falls to zero as shown in Fig. 2.10(c).

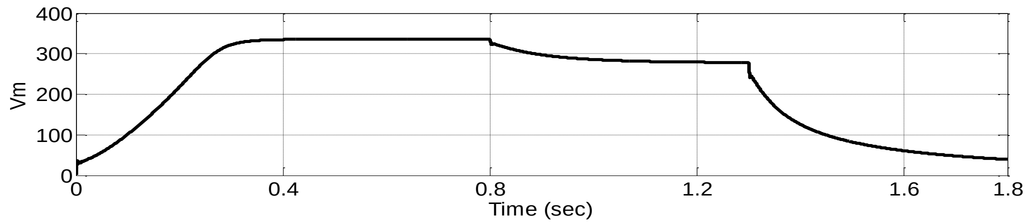


Fig. 2.10(a) SEIG peak voltage waveform

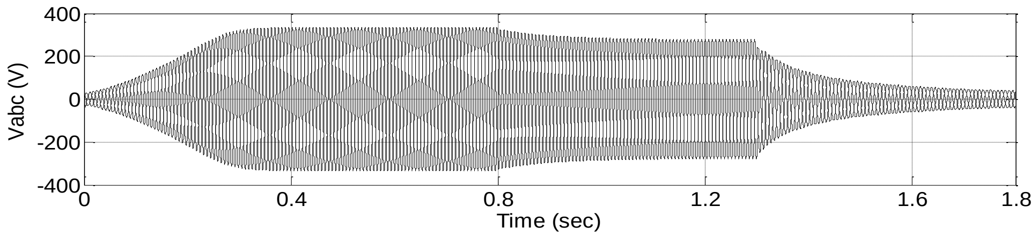


Fig. 2.10(b) SEIG terminal voltage (phase)

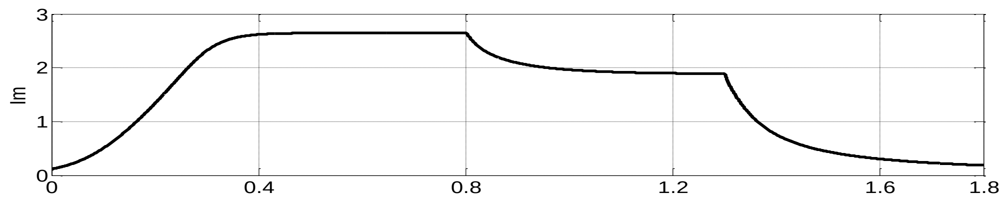


Fig. 2.10(c) Magnetizing current waveform

2.5.4 Step change in prime mover speed

When rotor speed changes from 157 rad/s to 165 rad/s at 0.6 sec by prime mover, the mechanical input from prime mover increases and this causes the increase in stator terminal voltage as illustrated in Fig. 2.11(a). The peak steady-state voltage increases from 335 V to 365 V. Fig. 2.11(b) shows the magnetizing voltage waveform, which increase from 2.6 A to 3 A.

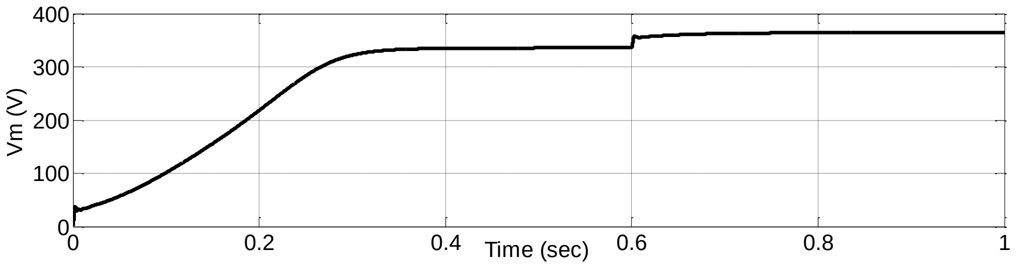


Fig. 2.11(a) SEIG peak voltage waveform

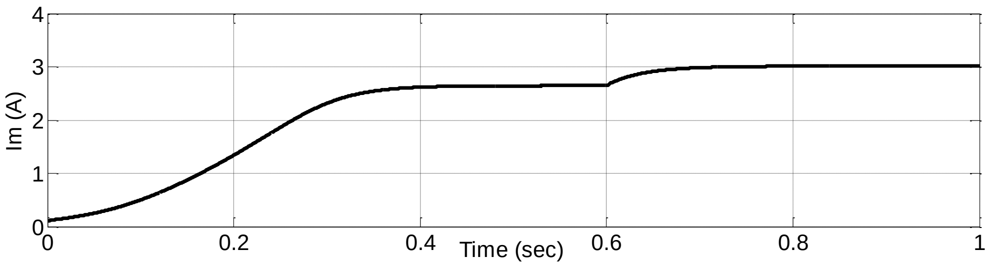


Fig. 2.11(b) Magnetizing current waveform

Fig. 2.12 illustrates the steady-state waveform of SEIG terminal voltage with peak value of 335 V and SEIG line for phase ‘a’ with peak value of 6.8 A

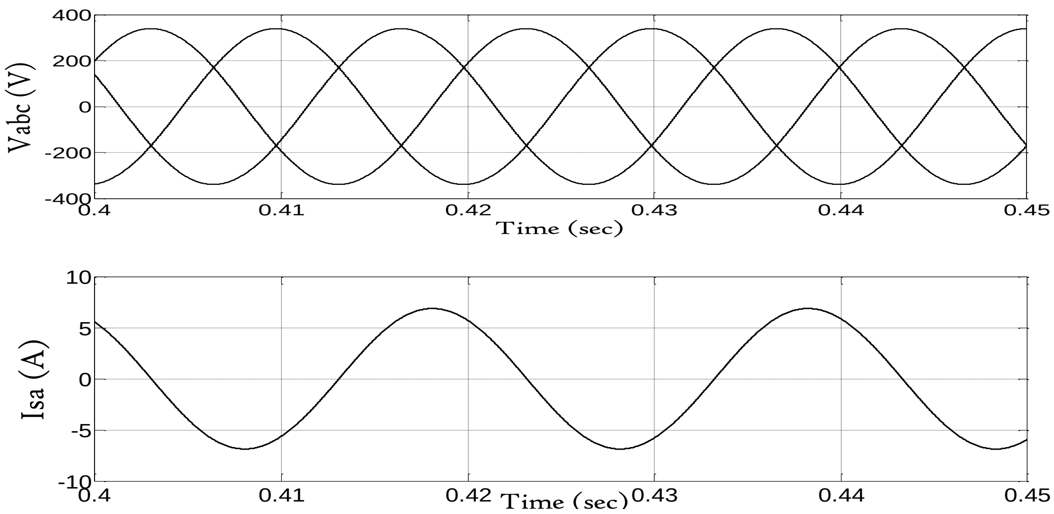


Fig. 2.12 Steady state waveform during voltage build-up

2.6 Conclusion

The self-excitation process of SEIG depends on load, capacitance value and speed of rotor. For maintaining the voltage of SEIG constant at its rated value a controller is required. The standalone system controller should be such that it is simple, reliable, low cost, easy to implement and has faster response. Thus, controller is required to develop by taking non-linear and linear load.

Chapter-3

MODELLING OF STATCOM BASED VOLTAGE CONTROLLER FOR SEIG DRIVEN BY CONSTANT SPEED PRIME MOVER USING CONVENTIONAL PI CONTROLLER

3.1 Introduction

In chapter 2, we have seen that will sudden application of load or change in rotor speed causes the variation in SEIG terminal voltage. For regulating voltage various controllers are developed by researchers [15]-[28]. Earlier attempts were made for regulating the voltage of SEIG by using thyristor controlled inductor and fixed capacitor [20], and short-shunt connections of capacitor [21]. But the voltage control provided by this type of controllers are discrete in nature and produces harmonics in the voltage waveform. With the advent of solid state devices, the control of SEIG terminal voltage has become more effective and reliable, as it can provide variable reactive power to generator and load to keep the terminal voltage constant with varying load conditions. Geng e.al. [23] Proposed the direct voltage control (DVC) strategy using PI regulator with a feed-forward compensator and lead-lag corrector. But its implementation is very complex because of design of lead-lag corrector and complexity involve in feed-forward compensator. Singh et al. [38] has proposed a static synchronous series compensator (SSSC) and static compensator (STATCOM) to feed static and dynamic load. These controllers are not designed for non-linear loads, also the dynamic response of controller is very poor.

This chapter present the analysis and development of STATCOM based voltage regulator for SEIG using conventional PI Controller feeding balanced or unbalanced load or linear and non-linear loads. The STATCOM eliminates the harmonics present in the system, it also provide load balancing and reactive power fulfilment as demanded by load and generator.

3.2 About STATCOM

The STATCOM consist of three phase current controlled voltage source inverter (CC-VSI) with IGBTS used as switches, a dc bus capacitor, ac inductors (for removing harmonics) and two conventional PI controller. The excitation capacitors in SEIG are used to generate the rated voltage of SEIG at no load. When load is applied, the additional demand of reactive power of load is fulfilled by STATCOM. The STATCOM acts as source of leading or lagging power supply depending on loading conditions. The dc bus capacitor act as energy storage device and provide reactive power as demanded by load. The block diagram of STATCOM with SEIG 7is shown in Fig. 2.1 along with control scheme applied to STATCOM for generating the gate signals.

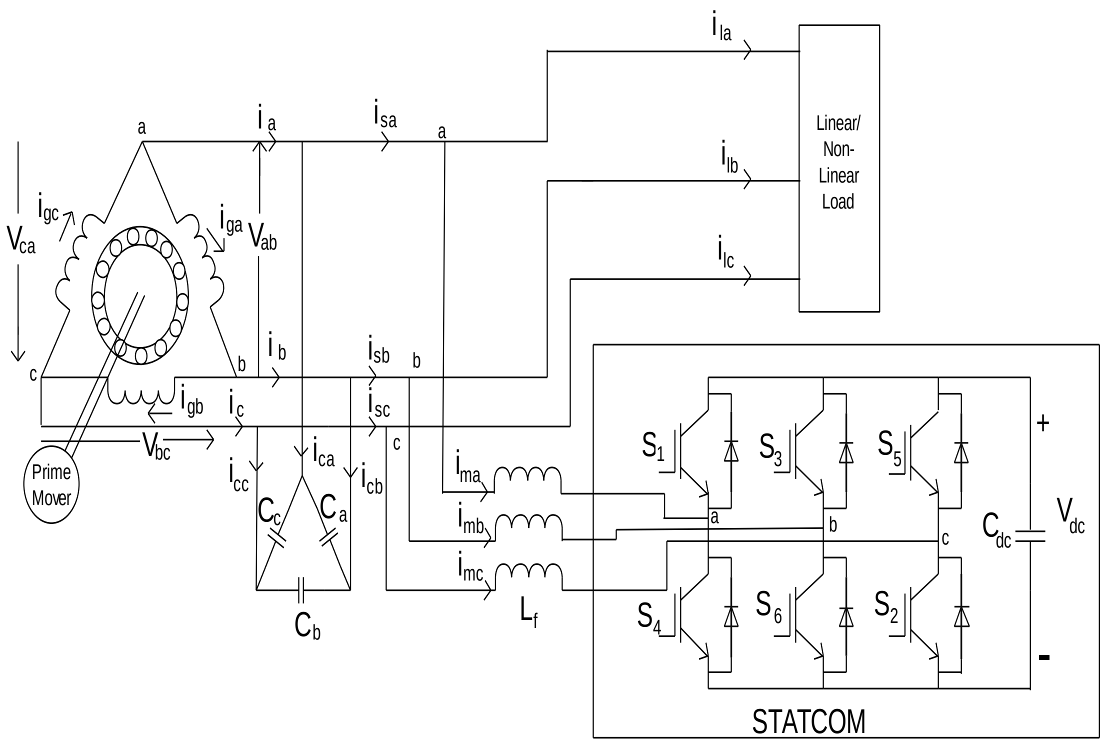
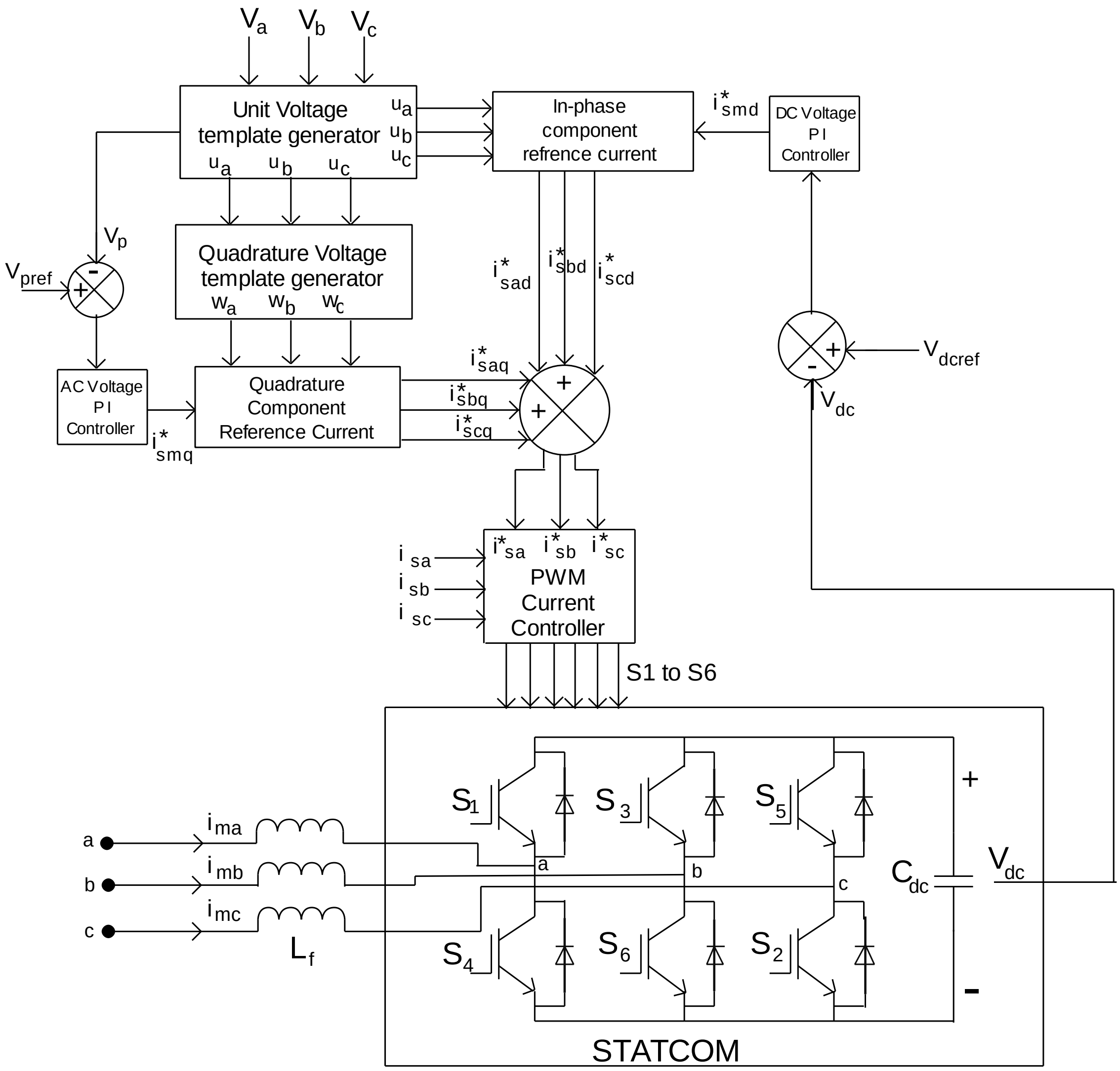


Fig. 3.1(a)



3.1(b)

Fig. 3.1 (a) Schematic diagram of SEIG-STATCOM system, (b) Control scheme applied to SEIG-STATCOM

3.2.1 Control scheme for SEIG

For controlling the voltage of SEIG, the source current is controlled which composed of two component in phase component and quadrature component. For maintaining the terminal voltage constant of SEIG, two control loops are deployed in STATCOM for generating reference supply current. The in-phase unit vectors are three phase sinusoidal functions of unit amplitude (u_a, u_b, u_c). These are computed by diving three phase ac voltage(v_a, v_b, v_c) by their amplitude V_p. The quadrature unit vectors are also three phase unit sinusoidal functions (w_a, w_b, w_c) , which are computed from in-phase vectors. There are two conventional PI controllers employed for maintaining the SEIG voltage constant. One PI controller sensed the input error, computed from the difference of reference ac voltage (V_{pref}) with amplitude of ac voltage (V_p). The output of obtained from this ac PI controller is taken as reference peak value of quadrature supply current component (i^*_{smq}), this current (i^*_{smq}) decided the amplitude of reactive current which is generated by the STATCOM. The quadrature unit vectors (w_a, w_b, w_c) are multiplied with the output of ac voltage PI controller (i^*_{smq}) which generates the quadrature component $(i^*_{saq}, i^*_{sbq}, i^*_{scq})$. of the reference supply current. The STATCOM uses capacitor as a dc bus which provided necessary reactive power requirement to the SEIG. The value of capacitor voltage (V_{dc}) is sensed and fed to comparator along with the dc reference voltage (V_{dcref}). The error is given to another conventional PI controller known as dc PI controller. The output of this PI controller yields reference peak in-phase supply current component (i^*_{smq}). This component (i^*_{smq}) decides the amplitude of the active power component of source current. The in-phase component $(i^*_{sad}, i^*_{sbd}, i^*_{scd})$ of reference supply current are generated by the multiplication of in-phase (u_a, u_b, u_c) unit vectors with the output of dc PI controller. The sum of quadrature $(i^*_{saq}, i^*_{sbq}, i^*_{scq})$ reference current and in-phase $(i^*_{sad}, i^*_{sbd}, i^*_{scd})$ reference current gives the reference source current $(i^*_{sa}, i^*_{sb}, i^*_{sc})$. The reference source currents then compared with the sensed source line currents $(i_{sa}, i_{sb}, and\ i_{sc})$ and the error is given to pulse width modulation (PWM) current controller to generate switching signals for IGBTs used in VSI.

Non-linear loads draw non-sinusoidal currents which composed of both fundamental as well as harmonics components of current. This non-sinusoidal current causes to inject harmonics in the systems and resulting in distortion of terminal voltage. Unbalanced loads draws unbalanced currents (composed of negative and positive sequence components) due to which the machine has to be used under derated condition. But the STATCOM filter out the harmonics and balances the unbalanced load, resulting in sinusoidal voltage and current of SEIG and also regulating its terminal voltage.

3.3 Modelling of SEIG-STATCOM

The SEIG-STATCOM system consist of SEIG, STATCOM, and the control technique involve and load. The dynamic model of each system components are discussed below.

3.3.1 Modelling of control scheme involved

The components of SEIG-STATCOM system are given in Fig. 3.1(a) and its control scheme applied to SEIG is illustrated in Fig. 3.1(b), which are modelled as follows

The SEIG terminal (v_a, v_b, v_c) phase voltages are sensed, which are sinusoidal in nature and their peak value is computed as follows

$$V_p = \sqrt{\left(\frac{2}{3}\right)(v_a^2 + v_b^2 + v_c^2)} \tag{24}$$

The in-phase unit vectors are computed as

$$u_a = \frac{v_a}{V_t}, \;\; u_b = \frac{v_b}{V_t}, \; u_b = \frac{v_b}{V_t} \tag{25}$$

The unit vectors in quadrature are derived from unit in-phase vectors as follows

$$\begin{bmatrix} w_a \\ w_b \\ w_c \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{\sqrt{3}}{2} & \frac{1}{2\sqrt{3}} & \frac{-1}{2\sqrt{3}} \\ \frac{-\sqrt{3}}{2} & \frac{1}{2\sqrt{3}} & \frac{-1}{2\sqrt{3}} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{26}$$

1) *Quadrature Component of Reference Source Currents*:
   The voltage error computed at nth sampling instant is

$$V_e(n) = V_{pref} - V_p(n) \tag{27}$$

Where, V_{pref} is peak of reference terminal voltage of SEIG and $V_p(n)$ is the amplitude of sensed SEIG terminal voltage at nth sampling. The output of ac PI controller ($i_{smq}^*(n)$) for regulating the SEIG terminal voltage at nth sampling instant is expressed as

$$i_{smq}^*(n) = \; i_{smq}^*(n-1) + K_{pac}\{V_{er}(n) - V_e(n-1)\} + K_{iac}V_e(n) \tag{28}$$

Where, K_{pac} and K_{iac} are proportional and integral gain constant of ac PI controller, $V_e(n)$ and $V_e(n-1)$ are voltage errors at n th and (n -1)th sampling instant respectively.

The $i_{smq}^{*}(n)$ is the amplitude of quadrature component of reference current computed at nth instant. Thus quadrature components of reference source currents are calculated as

$$i_{saq}^{*} = i_{smq}^{*} w_a; \quad i_{sbq}^{*} = i_{smq}^{*} w_b; \quad i_{scq}^{*} = i_{smq}^{*} w_c \tag{29}$$

2) *In-phase Component of Reference Source Currents*:

The dc bus capacitor voltage error computed at nth sampling instant is expressed as

$$V_{dce}(n) = V_{dcref} - V_{dc}(n) \tag{30}$$

Where, V_{dcref} is reference dc bus voltage, $V_{dc}(n)$ is the sensed dc bus voltage at nth sampling and $V_{dce}(n)$ is the voltage error at nth sampling instant. The output of dc PI controller at nth instant is expressed as

$$i_{smd}^{*}(n) = i_{smd}^{*}(n-1) + K_{pdc}\{V_{dce}(n) - V_{dce}(n-1)\} + K_{id} V_{dce}(n) \tag{31}$$

Where, K_{pdc} and K_{idc} are proportional and integral gain constant of PI controller of dc bus. The $i_{smd}^{*}(n)$ is the amplitude of active power component of source current. The in-phase components of reference source current are calculated as

$$i_{sad}^{*} = i_{smd}^{*} u_a; \quad i_{sbd}^{*} = i_{smd}^{*} u_b; \quad i_{scd}^{*} = i_{smd}^{*} u_c \tag{32}$$

3) *Evaluation of total source reference currents*:

For generating source reference currents, the in-phase reference current components and quadrature components of reference current are added together to generate the source reference current as follows

$$i_{sa}^{*} = i_{saq}^{*} + i_{sad}^{*}$$

$$i_{sb}^{*} = i_{sbq}^{*} + i_{sbd}^{*} \tag{33}$$

$$i_{sc}^* = i_{scq}^* + i_{scd}^*$$

4) *PWM Current Controller*:

The source reference current $(i_{sa}^*, i_{sb}^*, i_{sc}^*)$ and sensed source current (i_{sa}, i_{sb}, i_{sc}) are fed to comparator and error produced is amplified and given to PWM current controller. The PWM controller generates the switching pulses (ON/OFF) of the IGBTs of VSI. The current errors are calculated as

$$i_{saer} = i_{sa}^* - i_{sa}; \quad i_{sber} = i_{sb}^* - i_{sb}; \quad i_{scer} = i_{sc}^* - i_{sc} \tag{34}$$

These current error signals and a triangular carrier wave signal are fed to comparator to generate switching pulses for IGBTs. Corresponding to phase a (i_{saer}) if current error is greater in magnitude than the triangular carrier wave, the switch S_1 (upper device) of phase 'a' leg of VSI is turned ON and switch S_4 (lower device) of phase 'a' of VSI is turned OFF, and value of switching function FA is set to zero. If the current error is less in magnitude than the triangular carrier wave signal, then switch S_1 of VSI is turned OFF and switch S_4 is turned ON, and the value of FA is set to one. For other switches same logic same logic is applied for phase *'b'* (S_3 & S_6) and phase *'c'* (S_5 & S_2).

3.3.2 Modelling of STATCOM

The modelling of STATCOM is done as follows. The STATCOM bus voltage in derivative form is represent as

$$pv_{dc} = (i_{ca}FA + i_{cb}FB + i_{cc}FC)/C_{dc} \tag{35}$$

Where, SA, SB and SC are switching functions for ON/OFF positions of Voltage Source Inverter (VSI) switches $S_1 - S_6$.

The three phase ac line voltage of PWM conveter (f_a, f_b, f_c) which reflects from the dc bus voltage are expressed as

$$f_a = v_{dc}(FA - FB)$$

$$f_b = v_{dc}(FB - FC)$$

$$f_c = v_{dc}(FC - FA) \quad (36)$$

The voltage and current equations for the output of VSI of STATCOM are expressed as follows

$$v_a = R_f i_{ca} + L_f p i_{ca} + f - R_f i_{cb} - L_f p i_{cb} \quad (37)$$

$$v_b = R_f i_{cb} + L_f p i_{cb} + f_b - R_f i_{cc} - L_f p i_{cc} \quad (38)$$

$$i_{ca} + i_{cb} + i_{cc} = 0 \quad (39)$$

The value of i_{cc} obtained from equation (39) is substituted into equation (38) which gives

$$v_b = R_f i_{cb} + L_f p i_{cb} + f_b + R_f i_{ca} + L_f p i_{ca} + R_f i_{cb} + L_f p i_{cb} \quad (40)$$

By rearranging equations (37) and (40), we get

$$L_f p i_{ca} - L_f p i_{cb} = v_a - f_a - R_f i_{ca} + R_f i_{cb} \quad (41)$$

$$L_f p i_{ca} + 2L_f p i_{cb} = v_b - f_b - R_f i_{ca} - 2R_f i_{cb} \quad (43)$$

Hence, the STATCOM equations are obtained by solving (41) and (42)

$$p i_{ca} = \{(v_b - f_b) + 2(v_a - f_a) - 3R_f i_{ca}\}/(3L_f) \quad (44)$$

$$p i_{cb} = \{(v_b - f_b) - (v_a - f_a) - 3R_f i_{ca}\}/(3L_f) \quad (45)$$

3.3.3 Modelling of SEIG

The dynamic modelling of SEIG is already presented in chapter-2. Here it is again discussed in brief. The dynamic model is developed using stationary d-q reference frames, whose voltage equations are

$$[v] = [r][i] + [L]p[i] + W_g[G][i] \quad (46)$$

The current equation is derived from (46) and expressed as

$$p[i] = [L]^{-1}([v] - [r][i] - W_g[G][i] \quad (47)$$

Where

$[v] = [v_{qs}\ v_{ds}\ v_{dr}\ v_{qr}]^T$, $[i] = [i_{qs}\ i_{ds}\ i_{dr}\ i_{qr}]^T$, $= [r] = diag\ [r_s\ r_s\ r_r\ r_r]^T$

$$[L] = \begin{bmatrix} l_s + M & 0 & M & 0 \\ 0 & l_s + M & 0 & M \\ M & 0 & l_r + M & 0 \\ 0 & l_m & 0 & l_r + M \end{bmatrix}$$

$$[G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -M & 0 & l_r + M \\ M & 0 & l_r + M & 0 \end{bmatrix} \tag{48}$$

The electromagnetic torque of SEIG is given as

$$T_e = (\frac{3P}{4})L_m(i_{qs}i_{dr} - i_{ds}i_{dr}) \tag{49}$$

And torque balance equation is

$$T_{shaft} = T_e + J\left(\frac{2}{P}\right)pW_g \tag{50}$$

3.3.4 AC Line Voltage at PCC (Point of Common Coupling)

The q and d-axis stator currents (i_{qs} & i_{ds}) of SEIG are converted into three phase stator currents (i_{ga}, i_{gb}, i_{gc}) using Park's Transformation. From these phasor current, the line currents are calculated (i_a, i_b, i_c). The terminal voltage of SEIG in derivative form are given as

$$pv_a = \{(i_a - i_{la} - i_{ma}) - (i_b - i_{lb} - i_{mb})\}/(3C) \tag{51}$$

$$pv_b = \{(i_a - i_{lc} - i_{ma}) + 2(i_b - i_{lb} - i_{mb})\}/(3C) \tag{52}$$

$$v_a + v_b + v_c = 0 \tag{53}$$

Where, (i_{ga}, i_{gb}, i_{gc}) are SEIG phase currents, (i_a, i_b, i_c) are SEIG line currents, (i_{la}, i_{lb}, i_{lc}) are three phase load currents and (i_{ma}, i_{mb}, i_{mc}) are three phase STATCOM currents.

3.3.5 Linear Load Modelling

The linear load taken for study is star connected resistive load and resistive-inductive load. The modelling of RL load is expressed as

$$p[i_{sa} i_{sb}\ i_{sc}]^T = \frac{1}{L_l}[(v_a - v_{ca} - R_l i_{sa})\ (v_b - v_{cb} - R_l i_{sb})\ (v_c - v_{cc} - R_l i_{sc})]^T \quad (54)$$

3.3.6 Modelling of Non-linear load

The three phase diode rectifier with resistive load is taken as non-linear load. The circuit diagram is shown in Fig. 3.2. The three phase uncontrolled diode bridge rectifier with resistive load R_{rl} is taken as balanced non-linear load. The voltage across dc load (V_s) would be maximum terminal line voltage of SEIG. The rectifier dc load current is obtained as

$$i_d = i_{rl} = V_s/R_{rl} \quad (55)$$

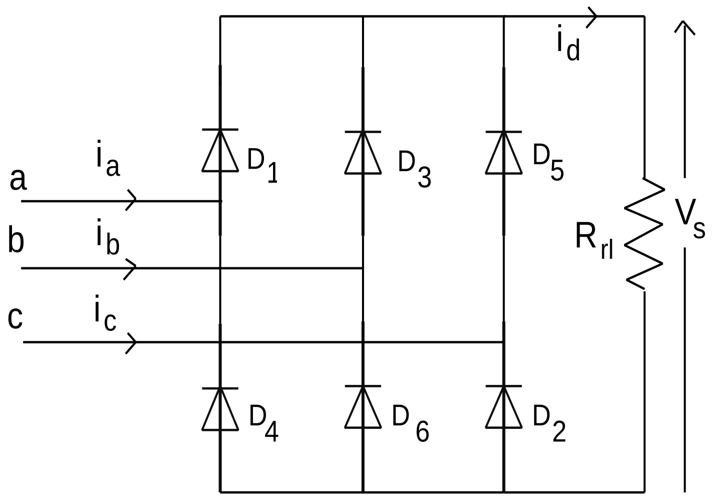


Fig. 3.2 Three-phase diode rectifier with R-load

3.4 Simulation of SEIG-STACOM with PI Control in MATLAB/SIMULINK

The model of SEIG-STATCOM with Conventional PI controller is simulated in MATLAB/Simulink. Initially SEIG is allowed to induce its terminal voltage by excitation capacitors. Then STATCOM is connected to SEIG but pulses to VSI controller is not given. The dc bus capacitor gets charges to SEIG terminal voltage value. Then load is connected which reduces the SEIG terminal voltage, after that gate pulses are given to switches of VSI and voltage is restored to their initial values. The values of various parameters of STATCOM is given below. Fig. 3.3 shows the Simulink model of SEIG-STATCOM and Fig. 3.4 shows the subsystem of controller.

L_f(H)	C_{dc}(F)	K_{pa}	K_{ia}	K_{pd}	K_{id}
50e-3	200e-6	0.0258	1.2	0.09	1.1

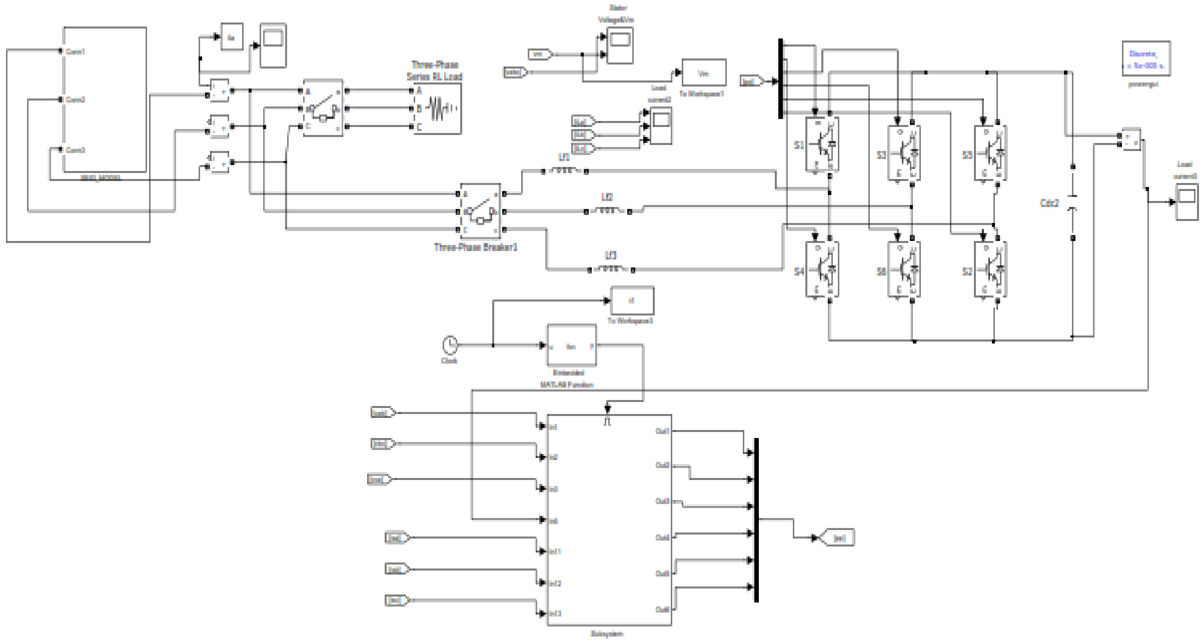


Fig.3.3 Simulink diagram of SEIG-STATCOM

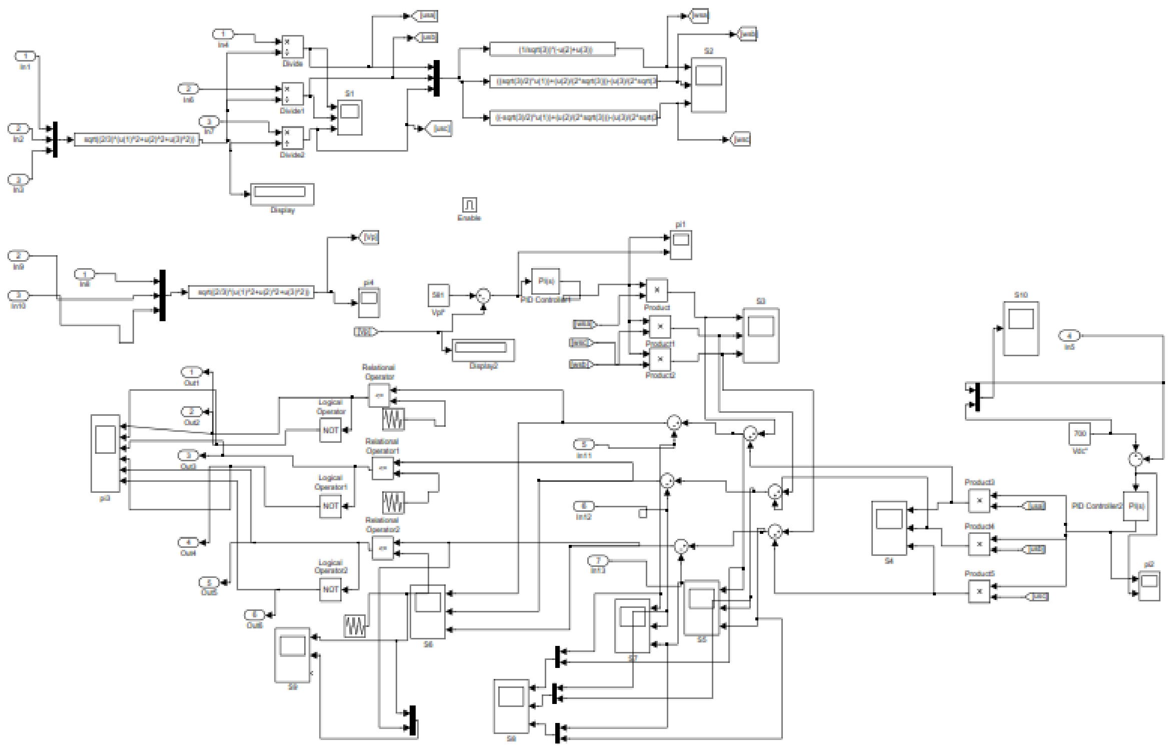


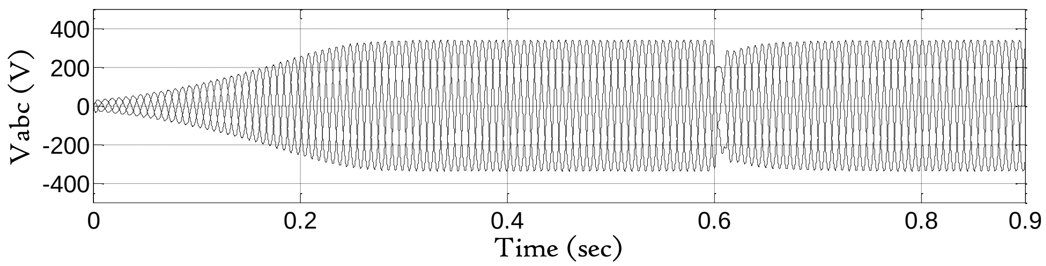
Fig.3.4 Subsystem of Controller

3.5 Result and Discussion

For simulation a 3.7kW, 415V, 7.5A, 4-Pole, 3-phase squirrel cage induction machine is used as generator. Different transient waveforms are illustrated to show the performance of proposed voltage control scheme supplying balanced/unbalanced linear/non-linear load. The result under various conditions are discussed below.

3.5.1 Voltage Build-up and Switch on STATCOM

Under voltage build up condition, first SEIG is excited using capacitor and voltage is build up, then STATCOM is connected but gate pulses to switches of VSI are not given. Fig. 3.5 shows the transient waveforms during voltage build up and, thereafter, switching in the STATCOM.



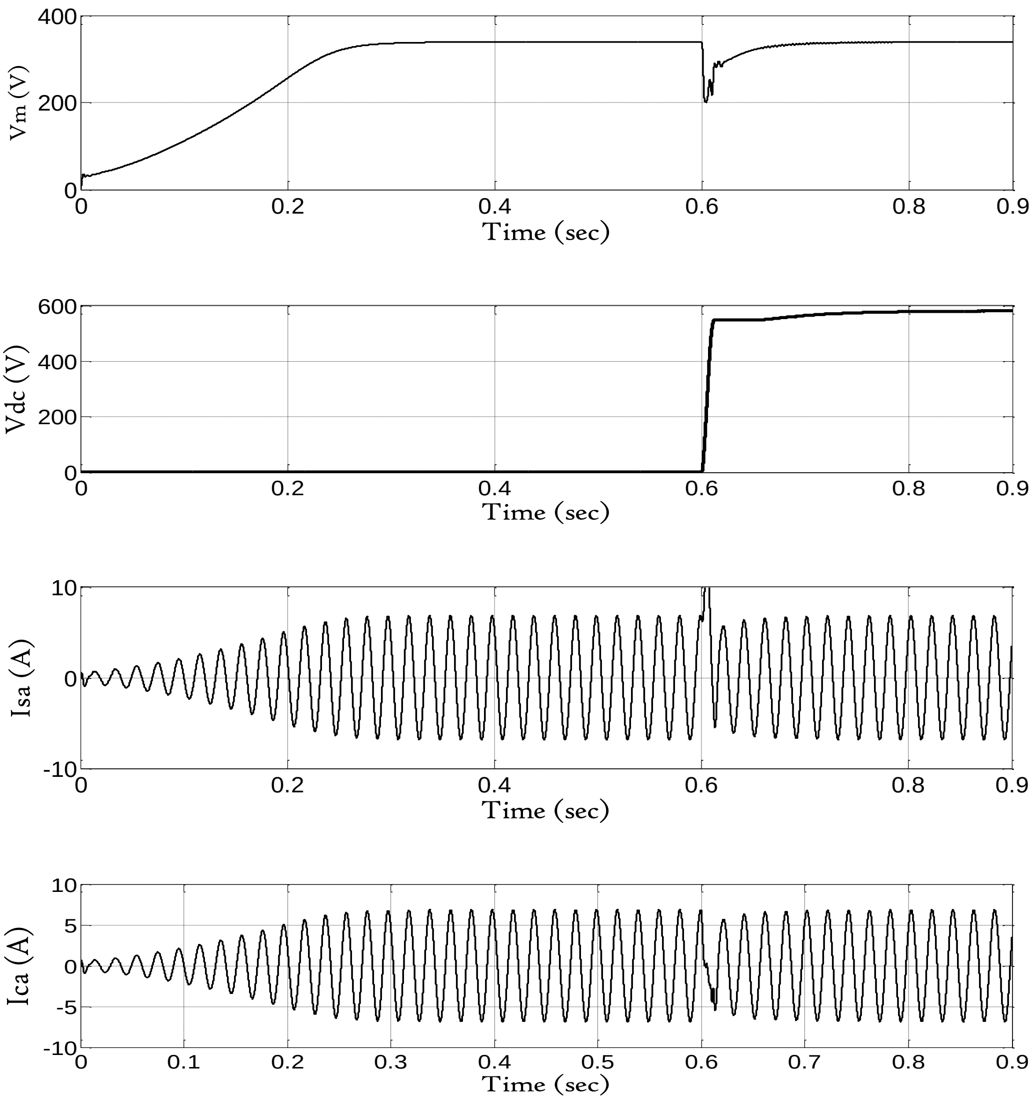


Fig. 3.5 Voltage build-up of SEIG and switching in STATCOM

Waveforms from top to bottom, respectively refers to SEIG terminal voltage (V_{abc}), peak of terminal phase voltage (V_m), dc bus capacitor voltage (V_{dc}), SEIG line current (I_{sa}) of phase 'a', Capacitor current (I_{ca}). For generating SEIG rated voltage at no load, excitation capacitor of value 61.6μF is connected in delta across the SEIG terminals. At 0.6 s STACOM is connected and dc bus capacitor of VSI gets charges to the 581 V (peak of ac voltage) through antiparallel diodes of VSI. With connection of STATCOM the terminal voltage momentarily drops but it gets to its rated value in few cycles.

Fig. 3.6 shows the steady state waveform of SEIG terminal voltage (V_{abc}) (335 V peak), Capacitor current (I_{ca}) (7.3 A peak) for phase 'a' and generator current (I_{sa}) (6.5 A peak), for SEIG-STATCOM system feeding 0.8 pf R-L load of 1.5 kW during voltage build-up process.

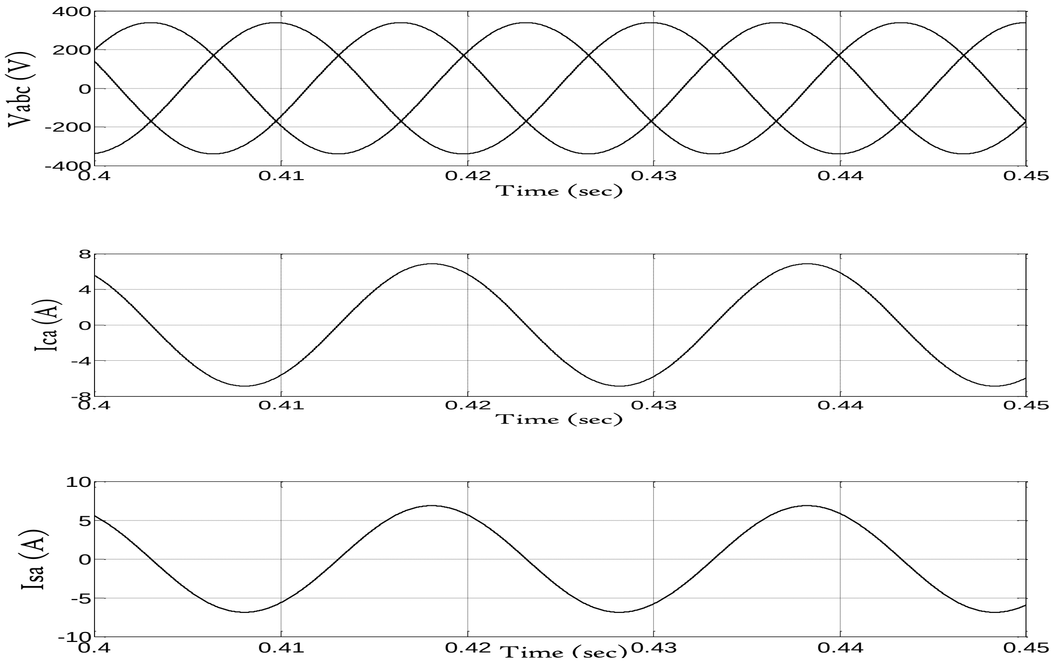
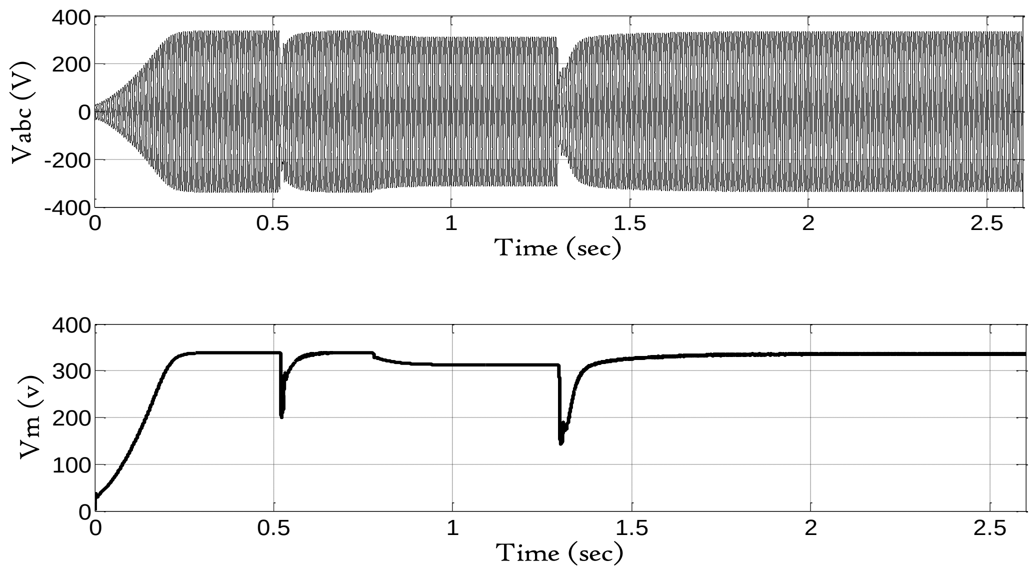
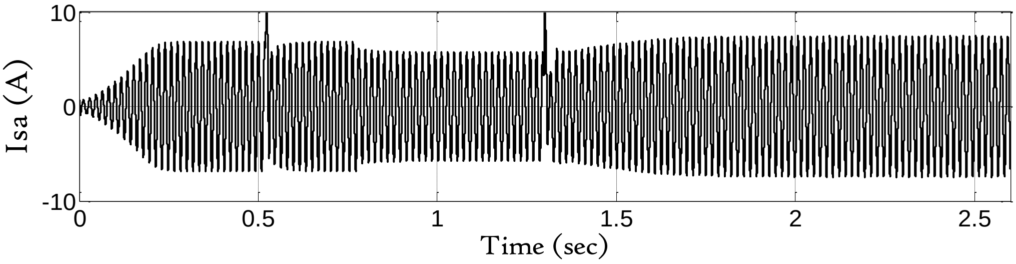


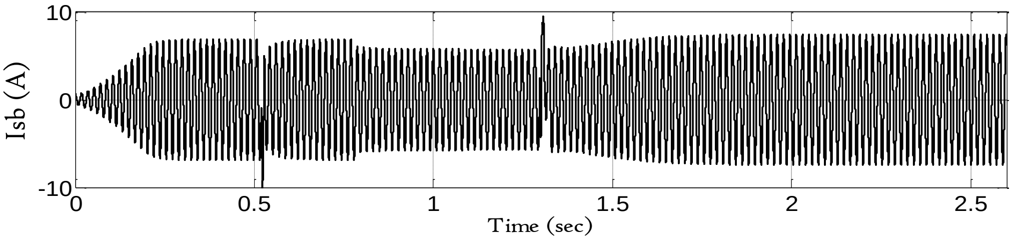
Fig. 3.6 Steady state waveforms during voltage build-up process

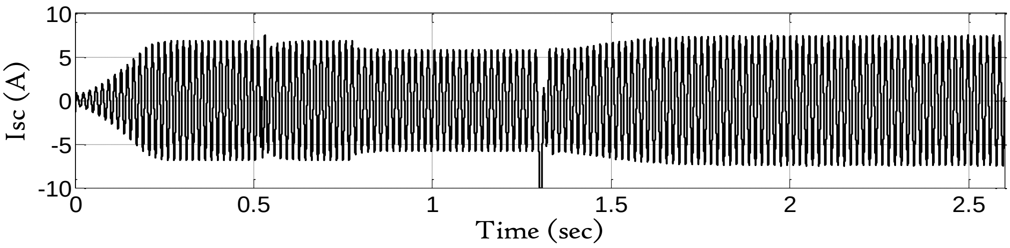
3.5.2 Connection of Load and Switching of Gate Pulses

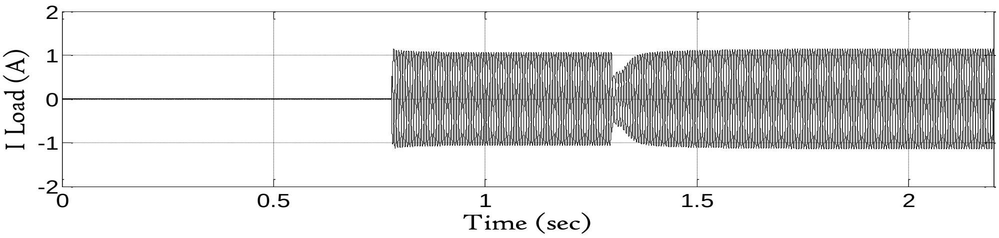
Initially, the SEIG is not loaded and gate pulses to IGBTs of VSI is not given. The SEIG reaches its rated voltage then load is connected and gate pulses to switches are given

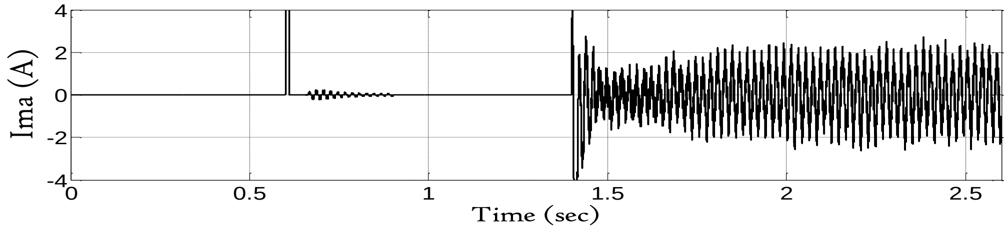


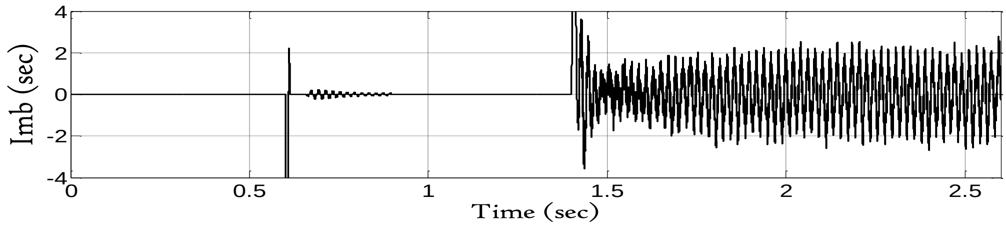

Isa (A)
Time (sec)
10
0
-10
0
0.5
1
1.5
2
2.5


Isb (A)
Time (sec)
10
0
-10
0
0.5
1
1.5
2
2.5


Isc (A)
Time (sec)
10
5
0
-5
-10
0
0.5
1
1.5
2
2.5


I Load (A)
Time (sec)
2
1
0
-1
-2
0
0.5
1
1.5
2


Ima (A)
Time (sec)
4
2
0
-2
-4
0
0.5
1
1.5
2
2.5


Imb (sec)
Time (sec)
4
2
0
-2
-4
0
0.5
1
1.5
2
2.5

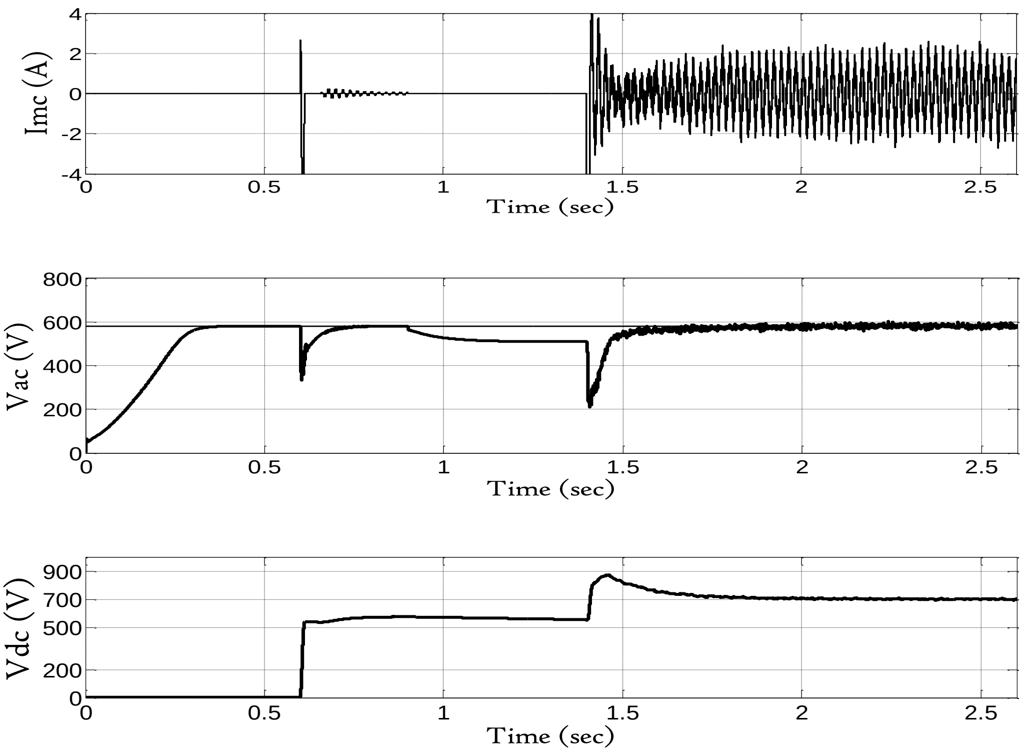
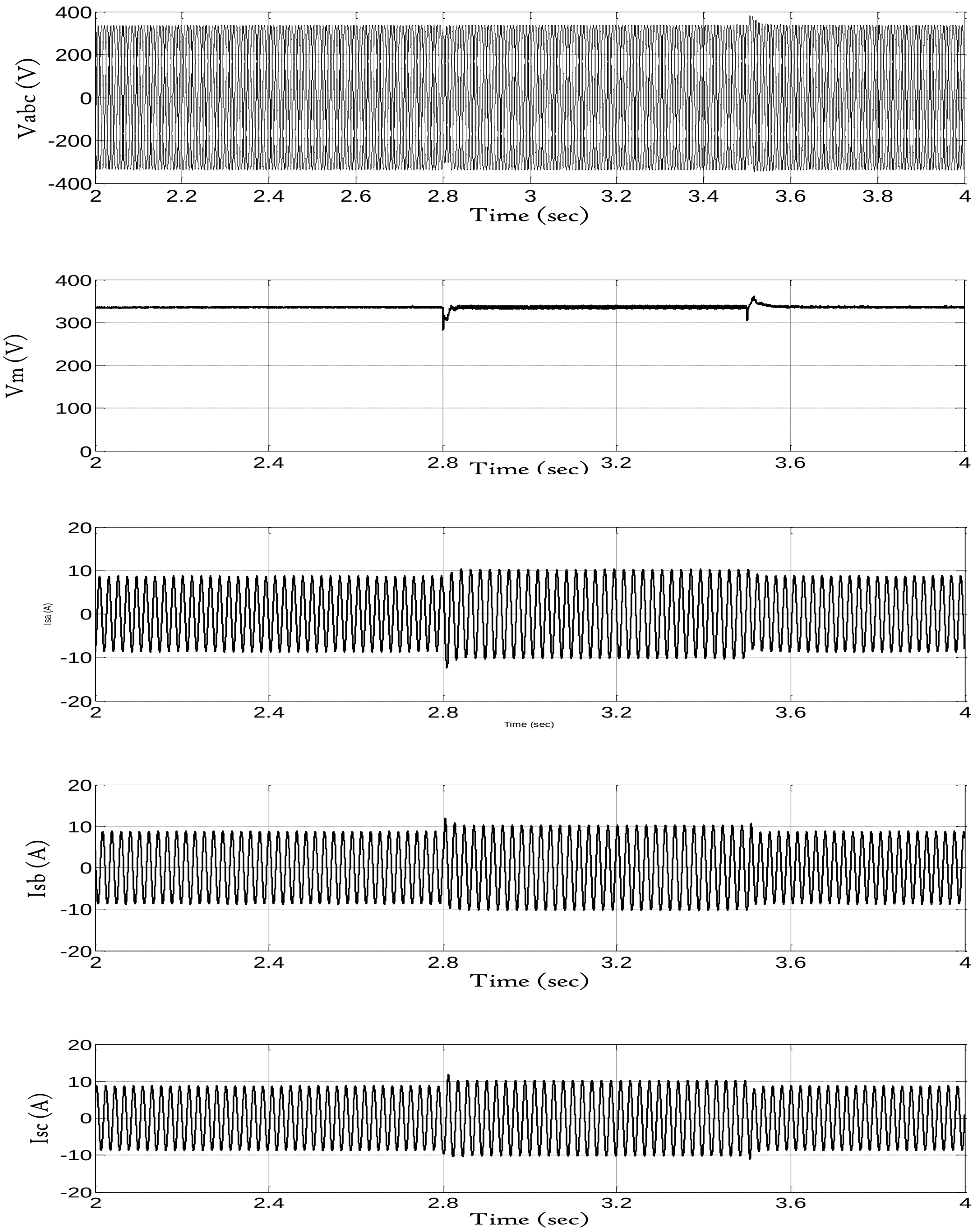


Fig. 3.7 Performance of SEIG-STATCOM with PI controller feeding 0.8 pf R-L load of 1.5 kW (at 0.6 s STATCOM is connected, load is connected at 0.9 s and gate pulses given at 1.4 s)

Fig. 3.7 depicts the performance characteristics of generator terminal voltage (V_{abc}), generator line currents (I_{sa}, I_{sb}, I_{sc}), three phase ac load current ($I_{Load\ abc}$), three phase STATCOM currents (I_{ma}, I_{mb}, I_{mc}), peak value of generator terminal voltage (V_p) and the reference value (V_{pref}) of ac voltage and the dc capacitor voltage (V_{dc}) along with its reference value (V_{dcref}) of dc capacitor voltage. At 0.9 s an R-L load of 1.5 kW at 0.8 pf is connected which result in fall of SEIG terminal voltage from its rated value. At 1.4 s gate pulses to IGBTs are given and control action of STATCOM is activated. A small transient in SEIG terminal voltage is observed with application of STATCOM. The generator supplies active power to STATCOM to charge its dc bus capacitor to its reference voltage (700 V) and the capacitor act as a source of reactive power to regulate terminal voltage of SEIG. The SEIG voltage again comes to its rated voltage (410 V, line to line). The generator and STATCOM current increases to supply active and reactive power as required by load.

3.5.3 Performance of SEIG-STATCOM with PI Controller feeding Resistive Load

The transient performance of generator terminal voltage (V_{abc}), generator line currents (I_{sa}, I_{sb}, I_{sc}), three phase load currents ($I_{load\ abc}$), three phase STATCOM current (I_{ma}, I_{mb}, I_{mc}), peak of generator phase voltage (V_p) with its reference value and dcapacitor voltage (V_{dc}) with its reference voltage are illustrated in Fig. 3.8 for a resistive load of 1.5 kW.



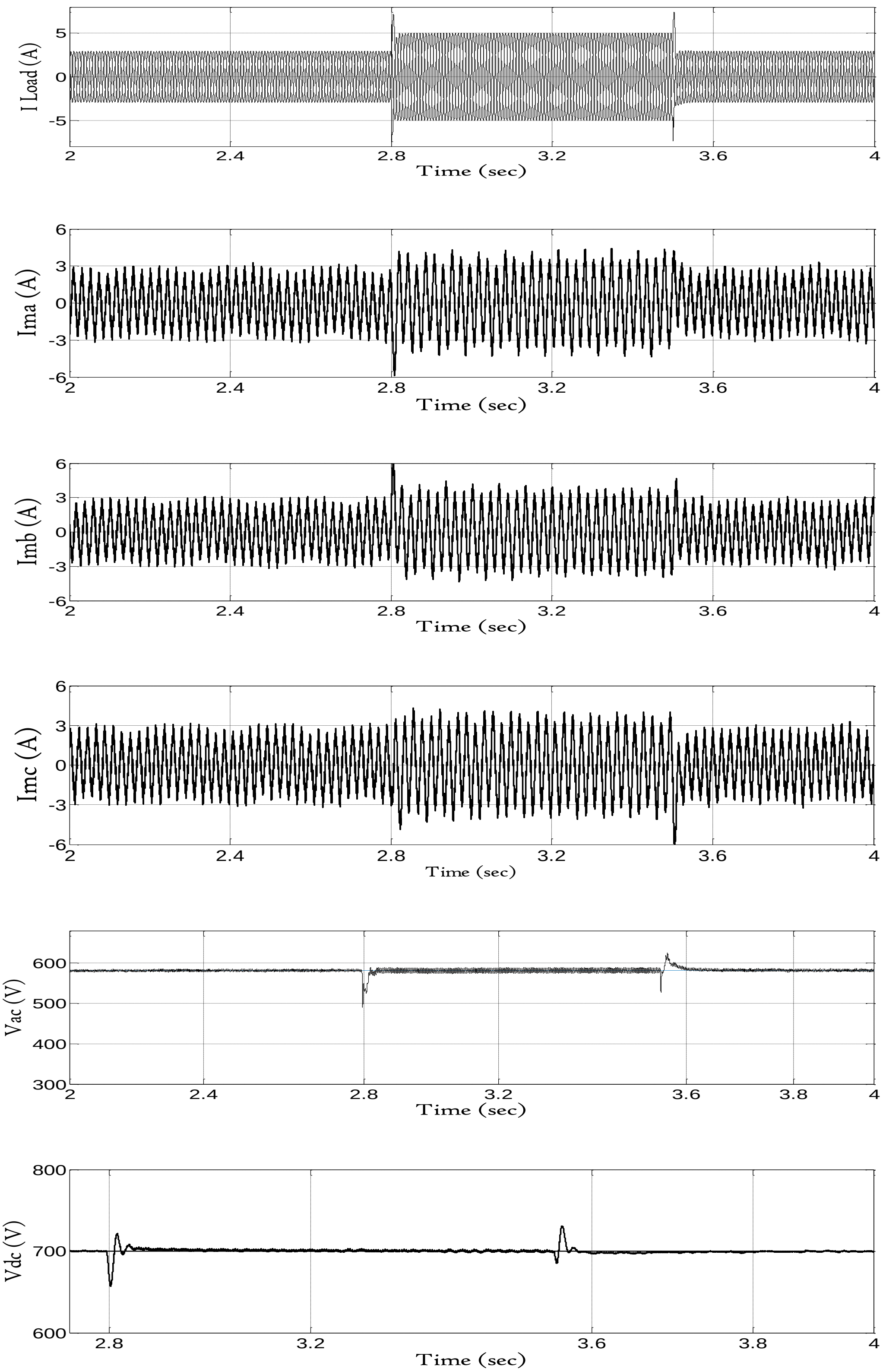


Fig. 3.8 Performance characteristics of SEIG-STATCOM system with PI controller supplying resistive load (The load increased from 1.5 kW to 2.5 kW at 2.8 s and decrease to 1.5 kW at 3.5 s)

The resistive load is changed from 1.5 kW to 2.5 kW at 2.8 s which result in increase in load current. The STATCOM current also increase which supplies the reactive power to maintain voltage constant. There is little transient in terminal voltage but it dies out quickly. With increase in load the dc bus voltage V_{dc} momentarily decreases, which supplies the reactive power to load, but returns to reference value (700 V) in few cycles. At 3.5 s, load is decrease from 2.5 kW to 1.5 kW which causes a drop in load current. The instantaneously generated surplus power is absorbed capacitor and hence an overshoot is observed in capacitor voltage which returns to reference voltage quickly with control action of dc PI controller. This decrease in loading results in decrease in SEIG current and STATCOM current with almost constant SEIG terminal voltage V_m(335 V peak).

The Steady state waveform of SEIG terminal voltage(V_{abc})(335 V peak), SEIG line current (I_{sa})(9 A peak) and load current ($I_{Load\ abc}$) (3.1 A peak) are depicted in Fig. 3.9 for SEIG-STATCOM system feeding resistive load of 1.5 kW

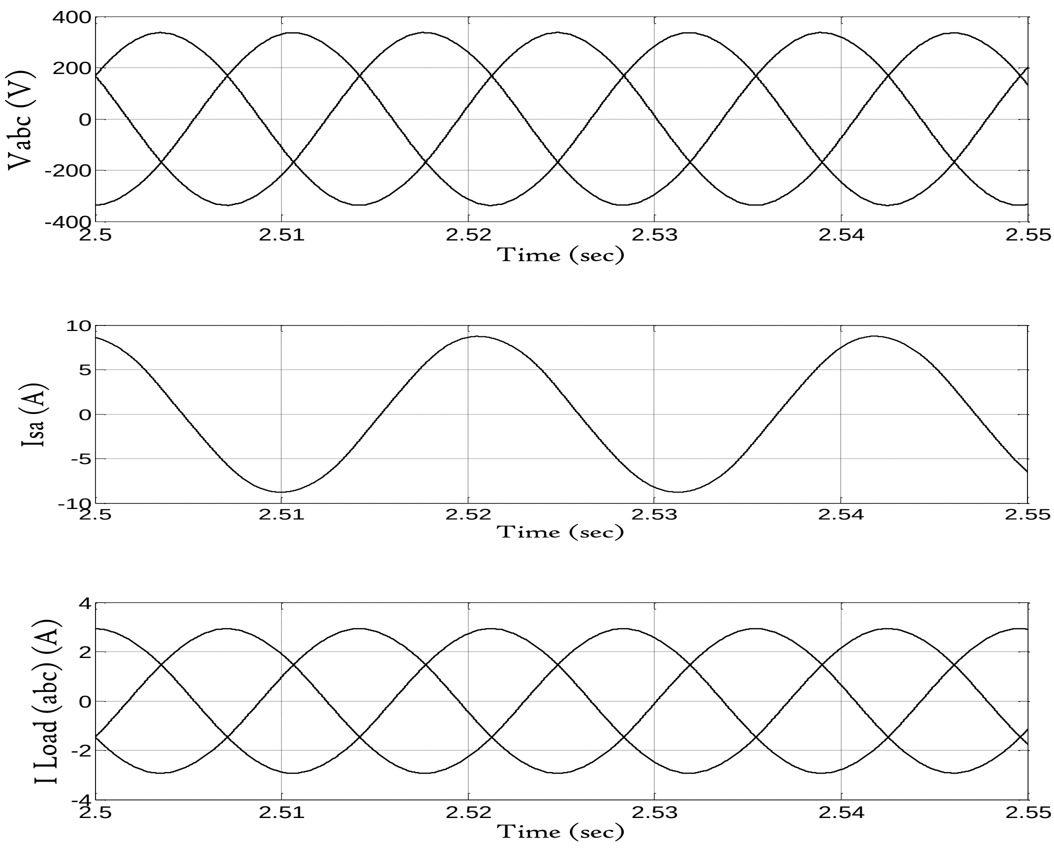
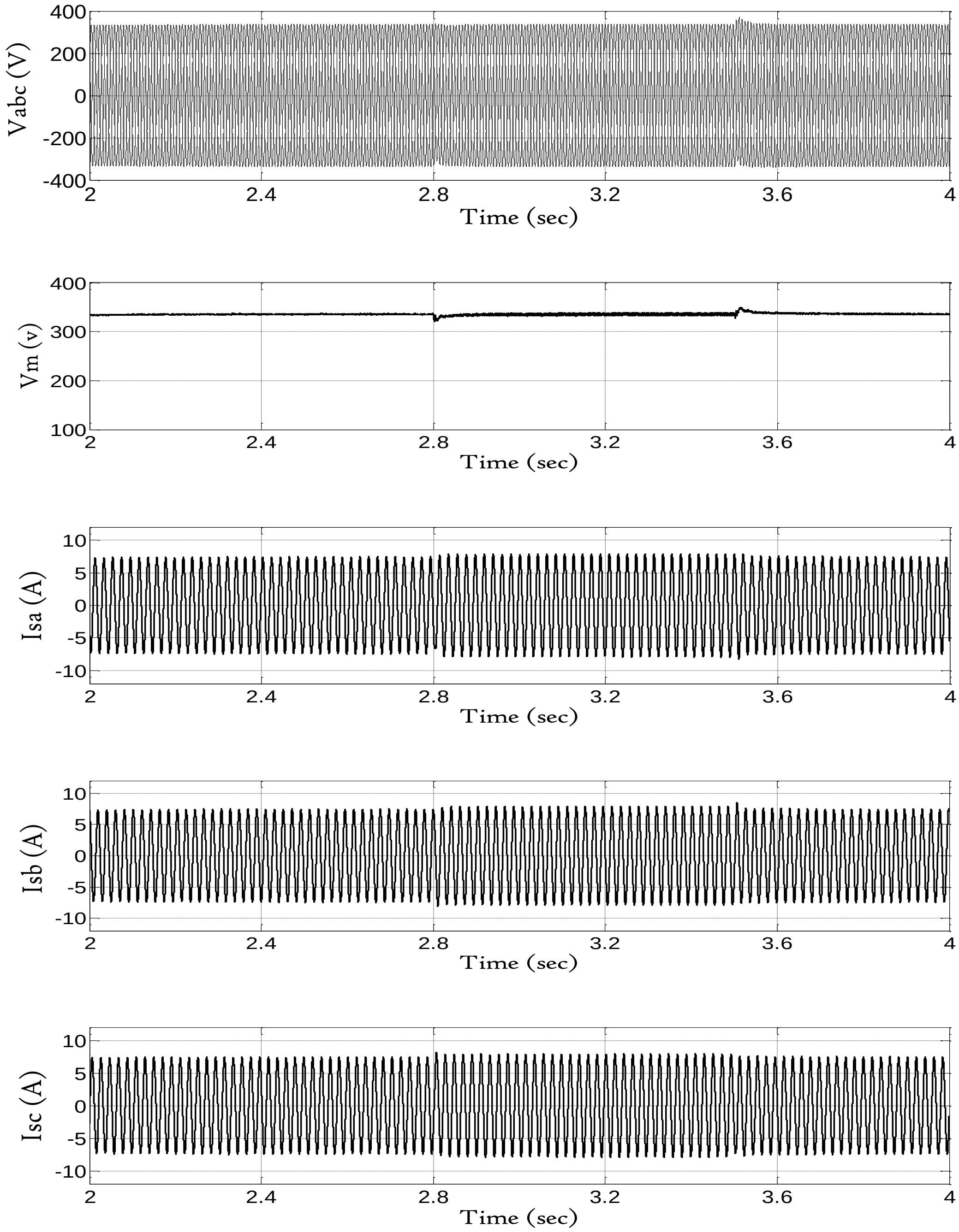


Fig. 3.9 Steady state waveform for SEIG-STATCOM system with PI controller feeding R load of 1.5 kW

3.5.4 Performance of SEIG-STATCOM with PI Controller feeding R-L Load

The performance characteristics of SEIG-STATCOM system feeding a 0.8 pf R-L load is shown in Fig. 3.10. Initially there is a load of 1.5 kW which changes to 2.2 kW.



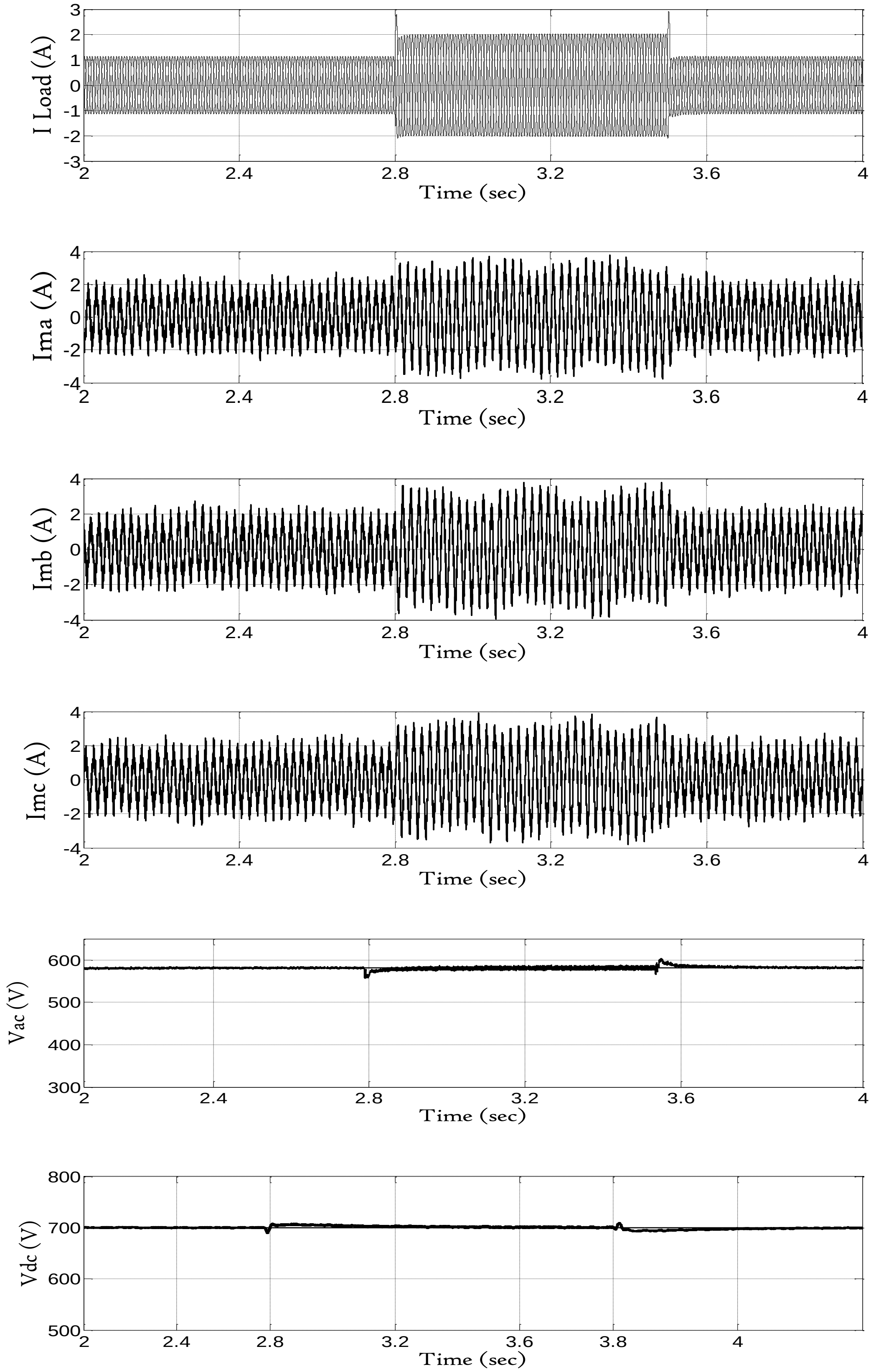
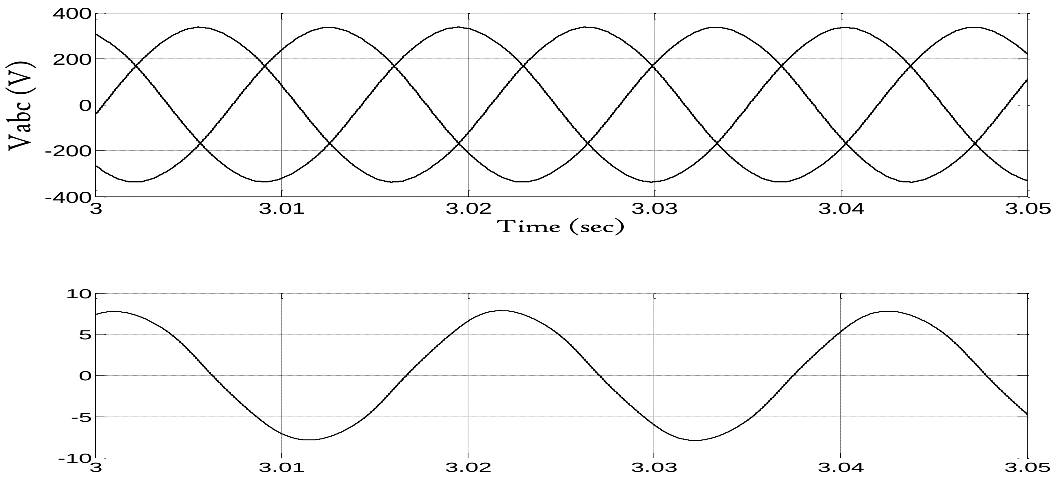


Fig. 3.10 Performance analysis of SEIG-STATCOM system with PI controller feeding 0.8 pf R-L load (Load is changed from 1.5 kW to 2.2 kW at 2.8 s and decrease to 1.5 kW at 3.5 s)

Waveforms from top to bottom, respectively relates to generator terminal voltage(V_{abc}), line currents (I_{sa}, I_{sb}, I_{sc}) of source, three phase load currents ($I_{load\ abc}$), three phase STATCOM current (I_{ma}, I_{mb}, I_{mc}), peak value of generated terminal voltage (V_p) along with its reference value and capacitor voltage (V_{dc}) along with its reference voltage. The load is changed from 1 kW to 2.2 kW at 2.8 s which causes increase in load current. The generated terminal voltage remains almost constant with small transients which quickly dies out. With increase in load the compensation current (i.e. STATCOM current) increases which supplies the increase reactive demanded by load. The SEIG current also increases which fulfil the active power requirement as demanded with increase in load. A small change in peak voltage V_{ac} is observed, but it returns to its reference voltage (581 V) after few cycles. The dc bus voltage V_{dc} also changes with application of load, but quickly return to reference value (700 V). The load is again reduced to 1.5 kW at 2.8 s which result in corresponding decrease in STATCOM currents and SEIG currents. The surplus generated power is now absorbed by dc bus capacitor as a results there is small variation in capacitor voltage, which settles to its reference value within few cycle. With sudden decrease in load, the peak ac terminal voltage V_{ac} increases from its set value and returns to reference value under PI control action.

Fig. 3.11 illustrates the steady-state waveforms of SEIG –STATCOM system depicting SEIG terminal voltage(V_{abc})(335 V peak), SEIG line current (I_{sa})(7.3 A peak) and load current waveform ($I_{Load\ abc}$) (2 A peak) feeding 0.8 pf R-L load of 2.5 kW



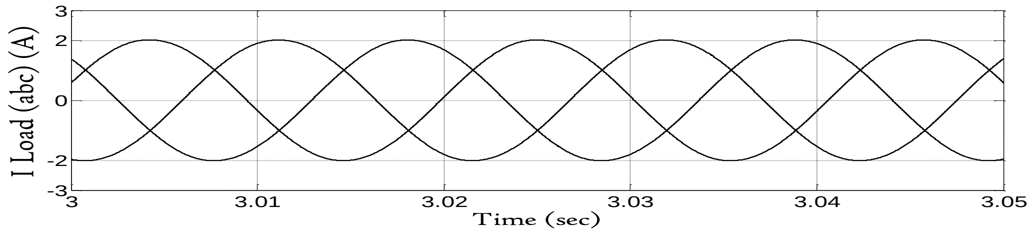
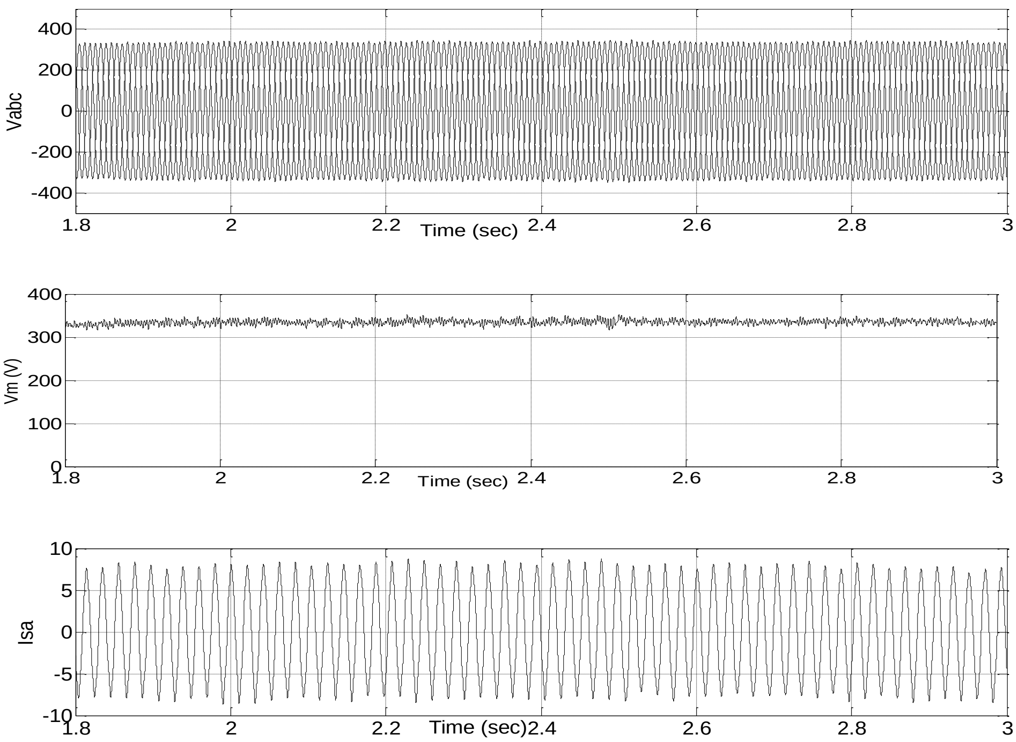
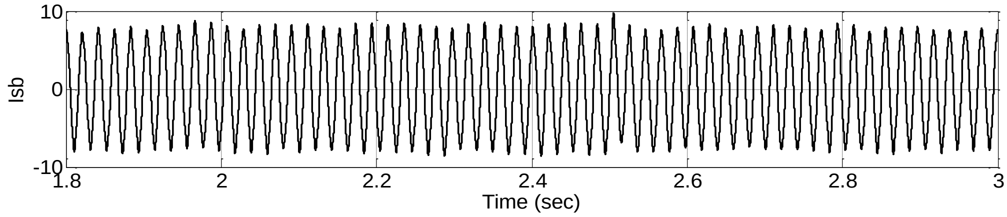


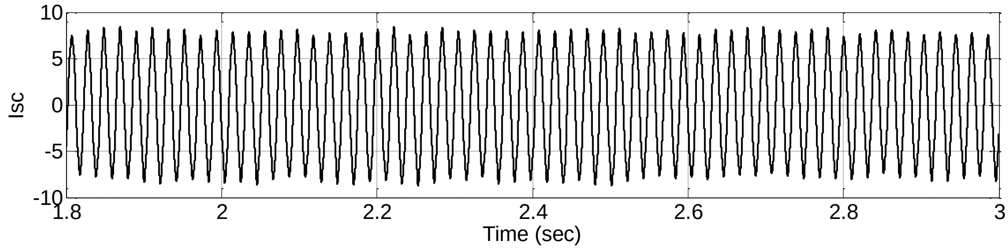
Fig. 3.11 Steady state waveform for SEIG-STATCOM system with PI controller feeding 0.8 pf R-L load of 2.5 kW

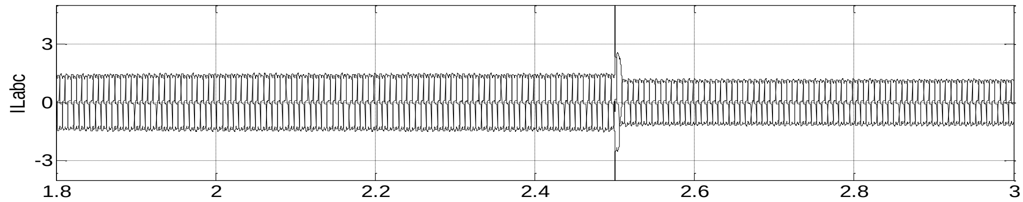
3.5.5 Performance of SEIG-STATCOM with PI Controller feeding Non-linear load (Three Phase Diode Rectifier with Resistive load)

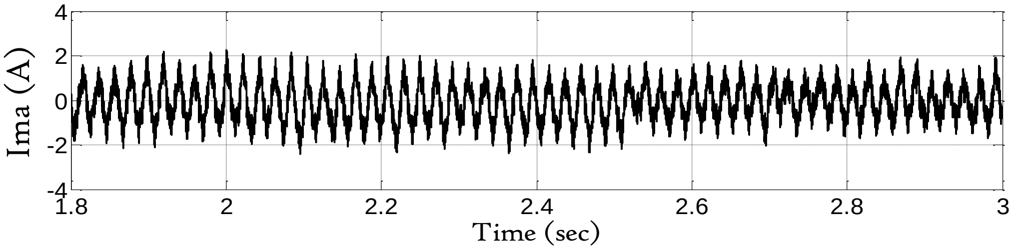
The simulated waveforms of generator terminal voltage(V_{abc}), line currents (I_{sa}, I_{sb}, I_{sc}), three phase load currents ($I_{load\ abc}$), three phase STATCOM current (I_{ma}, I_{mb}, I_{mc}), peak of ac terminal voltage (V_p) along with its reference value and capacitor voltage (V_{dc}) along with its reference voltage are illustrated in Fig. 3.12 for a three phase SEIG-STATCOM with PI control feeding ta non-linear load.

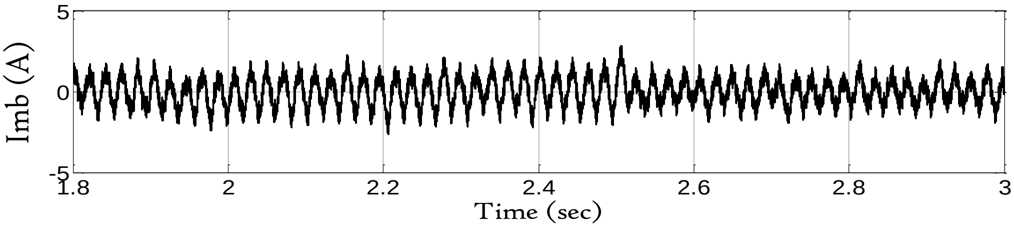


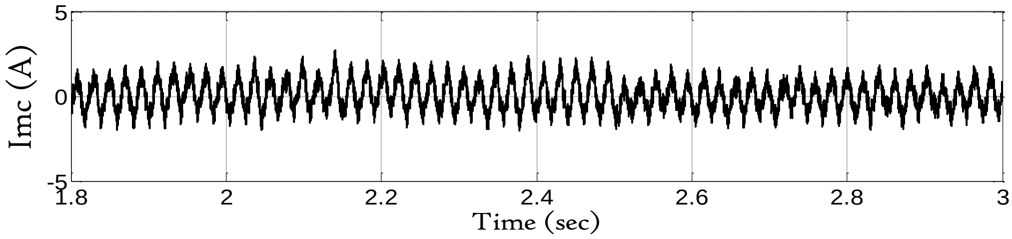

Isb
Time (sec)


Isc
Time (sec)


ILabc


Ima (A)
Time (sec)


Imb (A)
Time (sec)


Imc (A)
Time (sec)

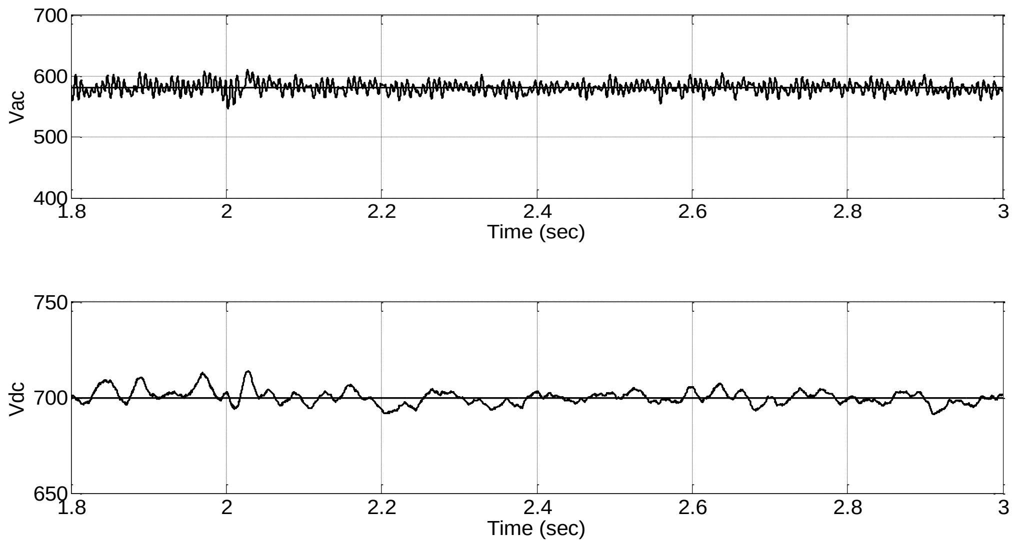
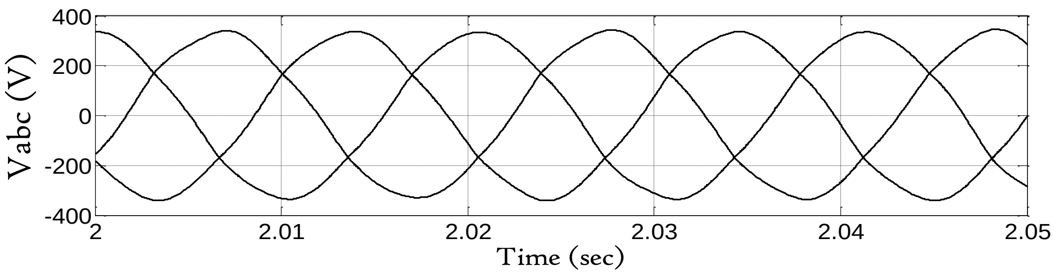


Fig. 3.12 Performance characteristics of SEIG-STATCOM system with PI controller feeding a non-linear load

(A three phase diode rectifier with resistive load change from 2 kW to 1.5 kW at 2.5 s)

Waveforms from top to bottom, respectively refers to generator terminal voltage(V_{abc}), line currents of source (I_{sa}, I_{sb}, I_{sc}), three phase load currents ($I_{load\ abc}$), three phase STATCOM current (I_{ma}, I_{mb}, I_{mc}), peak value of ac terminal voltage (V_p) along with its reference value and capacitor voltage (V_{dc}) along with its reference voltage. At 2.5 s, the resistive load on three phase diode rectifier is decrease from 2 kW to 1.5 kW. This result in decrease in generator, STATOR and load current to cut out the demand of reactive and active power to the load. With reduction in load value, small transient is observed in capacitor voltage which fulfil the reactive power demand of generator and load. The capacitor voltage settles to its reference value (700 V) within few cycles. With sudden decrease in load V_{ac} also increases from its set value and returns to reference value under PI control action.

The Steady state waveform of SEIG terminal voltage (V_{abc})(335 V peak), load current ($I_{Load\ abc}$) (1.5 A peak) and SEIG line current (I_{sa})(7.2 A peak) are depicted in Fig. 3.13 for SEIG-STATCOM system feeding non-linear load.



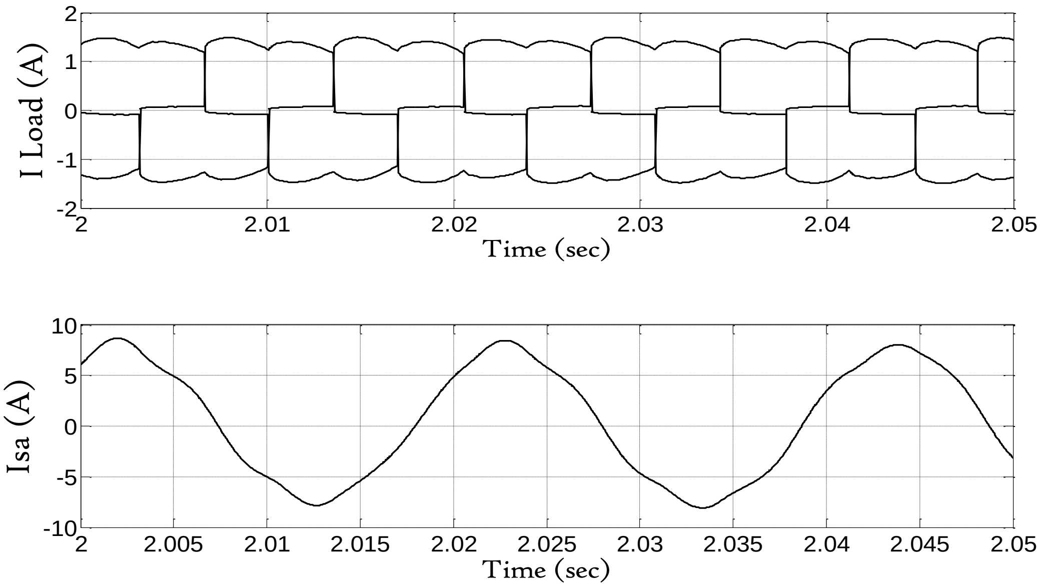


Fig. 3.13 Steady state waveform for SEIG-STATCOM system with PI controller feeding three phase diode rectifier with restive load of 2 kW

3.6 Conclusion

The modelling and simulation of SEIG with STATCOM have been carried out for linear and non-linear loads using conventional PI control. The proposed scheme for regulating voltage of SEIG is simple, efficient and easy to implement. From the simulated result, it has been found that the terminal voltage of generator remains constant irrespective of load. Whenever load is increased, either linear or non-linear, STATCOM supplies the compensated current for meeting the reactive power as demanded by load. For supplying the active power to load the generator current also increases. With decrease in load, the surplus generated power is absorbed by the capacitor of dc bus. When three phase rectifier load is connected, the STATCOM balanced the unbalanced load currents, and the generator currents but voltage remain balanced and sinusoidal at its rated value. Hence STATCOM acts as a load balancer. The STATCOM also eliminates the harmonics generated by non-linear load. Thus with application of STATCOM, the voltage regulation of SEIG improves by injection of compensation currents. It is also observed that the performance of conventional PI controller is quite satisfactory but it takes more time to reach its steady state value and the steady state performance is not smooth.

Chapter-4

MODELLING OF STATCOM BASED FUZZY VOLTAGE CONTROLLER FOR SEIG DRIVEN BY CONSTANT SPEED PRIME MOVER

4.1 General

Chapter-3 presents the modelling of STATCOM based voltage regulator for SEIG using conventional PI control but voltage regulation using STATCOM with conventional PI control has certain demerits [4]-[17]. The major demerit of conventional PI control requires mathematical model of the system. The conventional PI control cannot handle non-linearity as it is quite difficult to model a non-linear system. The conventional PI control are also sensitive to parameter variation and they cannot work with imprecise and noisy input. The PI control has poor dynamic response and noisy steady state response as seen in chapter 3. This chapter deals with the modelling of STATCOM using Fuzzy controller with which eliminates all demerits of conventional PI control [26]- [28].

This thesis illustrate the design of Mamdani type Fuzzy controller for STATCOM for regulating the SEIG voltage. The merits of using Fuzzy controller system over conventional PI system are as follows

a) Fuzzy control does not require exact mathematical model
b) Fuzzy controller is based on simple linguistic information and thus easy to understand
c) It does not require precise input, as it can work with imprecise and noisy input
d) Fuzzy controller is insensitive to parameter variation as it does not require accurate mathematical model
e) Fuzzy controller offers more flexibility as it is easy to modify the functionality

4.2 Basic of Fuzzy Controller

Fig. 4.1 shows the basic inference system using fuzzy approach. Its major components are input, fuzzy system, and output. The output is evaluated by aggregating all rules. We can frame as many as rule depending on complexity of the system and its ease to implement.

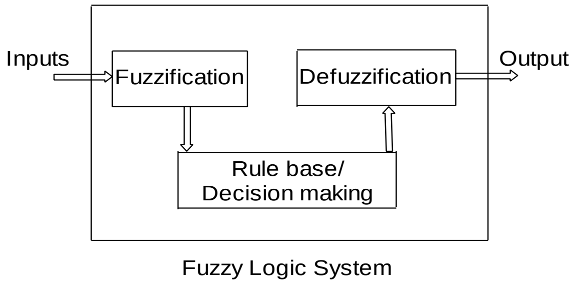


Fig. 4.1 Basic components of Fuzzy controller

Step I: Fuzzification

Fuzzy logic converts the numerical variables into linguistic variables. But the variables are available are real numbers. The method of transforming a numerical variable (real number) into linguistic variable is called fuzzification. It is the first step to select no. of inputs and assign linguistic variables to each input and membership function to them with suitable numerical values. The membership functions are represented by different shapes such as triangular, trapezoidal, Gaussian, etc. but generally triangular is used because of its simplicity.

Step II: Formation of rule base

This step form the rule of controller to control the action taken from knowledge of control rules and linguistic variable. It has three different components as follows

a) IF (predecessor and antecedent) –use of fuzzy operator in it.
b) THEN part of rule-suggestion or inference from antecedent part to the subsequent part.
c) Aggregation (accumulation) of the subsequent of all rules.

For decision making a specific set of rule base are formed which is based on human thinking in the form of IF-THEN rule. Then these rules can be aggregated using OR or AND operator. A total of $(m \times n)$ rules can be formed based on combinations of different inputs, where m is no. of inputs and n is number of membership functions for each inputs. Suppose that there are two inputs, input 1 has two membership function and input 2 has three membership functions, then a total of 6 rules can be framed.

Step III: Decision making

The rule framed above is required to be processed to take decision based on input information available. Fuzzy operator OR (MAX) is used to process the 'then' part. The And (MIN) can also be used. The various operators of Fuzzy logic are described below

1. AND- Intersection: $\tau_{A\cap B}(x)$ = min $[\tau_A(x), \tau_B(x)]$
2. OR-Union: $\tau_{A\cap B}(x)$ = max $[\tau_A(x), \tau_B(x)]$
3. NOT-Complement: $\tau_A(x)$ = 1-$\tau_A(x)$

Where $\tau_B(x)$ and $\tau_B(x)$ denote the degree of membership function of given element in fuzzy sets A and B

Step IV: Defuzzification

This is the conversion of linguistic fuzzy control variables to a non-fuzzy control action. The truncated output MFs obtained after implication of each rule are combined or aggregated to obtain final fuzzy output. The fuzzy output obtained after aggregation is converted to crispy value. This step is known as defuzzification. One method of defuzzification is finding centroid or centre of gravity of the area.

4.3 Modelling of STATCOM with Fuzzy Logic Controller

Recently, Fuzzy logic controllers have gained more attention and extensively used in various power electronic applications. The advantage of Fuzzy controllers over conventional PI controllers is that they don't require an exact mathematical model of the system and can work with imprecise and noisy inputs [18-19]. The conventional PI control take more time for computation as it takes more time for the settling of dc capacitor voltage. Therefore there is need to track the dc voltage to its reference value as fast as possible for better dynamic response. In this work, Mamdani type fuzzy controller has been implemented for STATCOM, which reduces the settling time of capacitor voltage waveform and reduces Total Harmonic Distortion. In this thesis through simulation result, it has been shown that Mamdani type fuzzy controller has improve the dynamic response of the system and has smooth steady state performance as compared to conventional PI control. The performance characteristics of Fuzzy logic controller is more robust and better than conventional PI controller with variation of load and parameter variations.

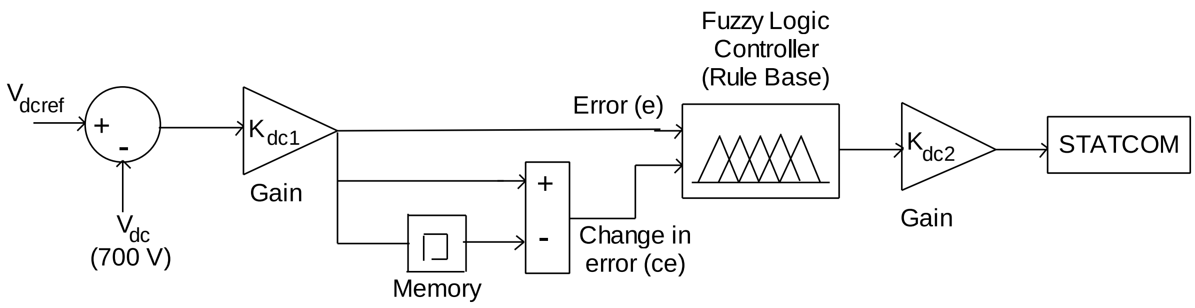


Fig. 4.2 Fuzzy control scheme for capacitor voltage control

Fig. 4.2 illustrates the fuzzy control scheme used in place of conventional PI control for capacitor voltage. The capacitor voltage (V_{dc}) is sensed from dc bus capacitor and compared with capacitor voltage (V_{dcref}, 700 V). The error signal generated from the difference of reference dc voltage and actual dc voltage is amplified. In case of fuzzy logic control scheme error (*e*) and change in error (*ce(n) = e(n)-e(n-1)*) are used as inputs for fuzzy controller. The output of fuzzy logic controller is amplified and taken as peak of d-axis current (i^*_{smd}) which multiplied with in-phase component of current (u, u_b, u_c) to give d-axis reference currents ($i^*_{sad}, i^*_{sbd}, i^*_{scd}$).

A memory block is used to calculate the change in error (*ce*) which gives one integration step delay. The characteristics of fuzzy controller used are as follows

a) Seven memebership functions are used for each input (*e* and *ce*) and output
b) Triangular functions are used for simplicity
c) Implication is done using Mamdani's 'min' operator
d) Defuzzification using 'Centre of Area (COA)' method

The seven member ship functions used for each input and output are as follows

a) BN-Big Negative
b) MN-Medium Negative
c) SN-Small Negative
d) ZE-Zero
e) SP-Small Positive
f) MP-Medium Positive

g) BP- Big Psitive

Thus a total of 49 (7×7) are framed as given in Table 1 below

ce / e	**BN**	**MN**	**SN**	**ZE**	**SP**	**MP**	**BP**
BN	BP	BP	BP	BP	MP	SP	ZE
MN	BP	BP	BP	MP	SP	ZE	SN
SN	BP	BP	MP	SP	ZE	SN	MN
ZE	BP	MP	SP	ZE	SN	MN	BN
SP	MP	SP	ZE	SN	MN	BN	BN
MP	SP	ZE	SN	MN	BN	BN	BN
BP	ZE	SN	MN	BN	BN	BN	BN

Table 1. Rule base table of fuzzy controller for STATCOM

Similarly for ac voltage control same method is adopted and control circuit is depicted in Fig. 4.3

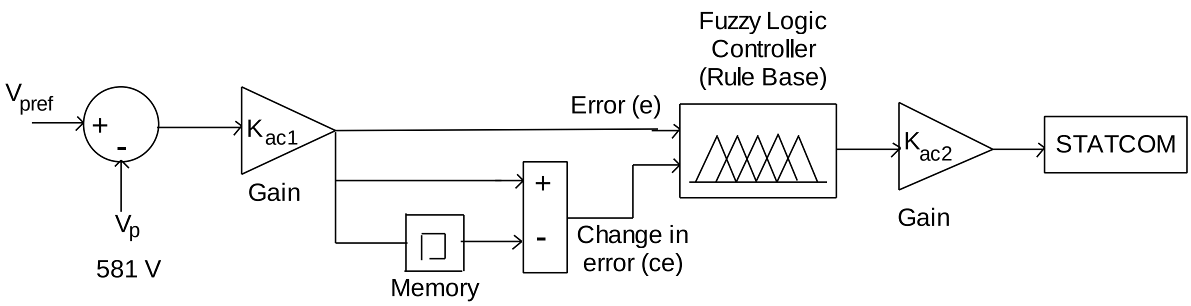


Fig. 4.3 Fuzzy control scheme for ac peak voltage control

Fig. 4.3 shows the fuzzy control scheme used for controlling the peak ac voltage in place of conventional PI control. The peak terminal voltage (V_p) is sensed reference ac voltage (V_{pref}, 581 V) are fed to comparator. The output of ac fuzzy controller is amplified and taken as peak of q-axis current (i^*_{smq}) which multiplied with quadrature component (w_a, w_b, w_c) of current to give q-axis reference currents ($i^*_{saq}, i^*_{sbq}, i^*_{scq}$). The rule base for ac fuzzy controller is same as of dc fuzzy controller. The d-axis reference current templates ($i^*_{sad}, i^*_{sbd}, i^*_{scd}$) and q-axis reference currents templates ($i_{saq}^*, i_{sbq}^*, i_{scq}^*$) are added to give three phase ($i_{sa}^*, i_{sb}^*, i_{sc}^*$) source reference currents. By comparing actual source currents ($i_{sa}, i_{sb}, and\ i_{sc}$) with m source reference current templates the gate pulse for switches are generated.

4.4 Simulation of SEIG-STACOM with Fuzzy Logic Control in MATLAB/SIMULINK

The model of SEIG-STATCOM with fuzzy Control is simulated in MATLAB/Simulink environment. Initially SEIG is allowed to induce its terminal voltage by excitation capacitors. Then STATCOM is connected to SEIG but pulses to VSI controller is not given. The dc bus capacitor gets charges to SEIG terminal voltage value. Then load is connected which reduces the SEIG terminal voltage, after that gate pulses are given to switches of VSI and voltage is restored to their initial values. The values of various parameters of STATCOM is given below.

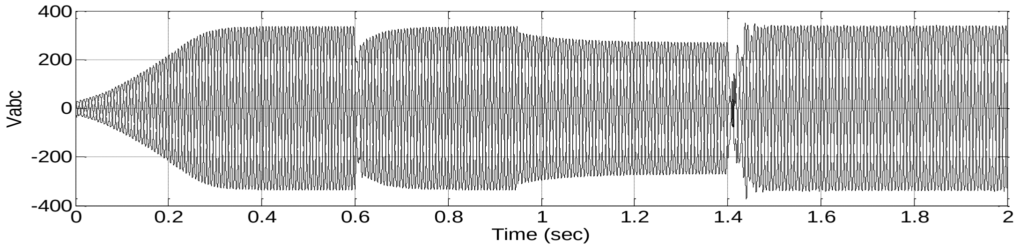
L_f(H)	C_{dc}(F)	K_{ac1}	K_{ac2}	K_{dc1}	K_{dc2}
50e-3	200e-6	1/8700	498	1/1400	310

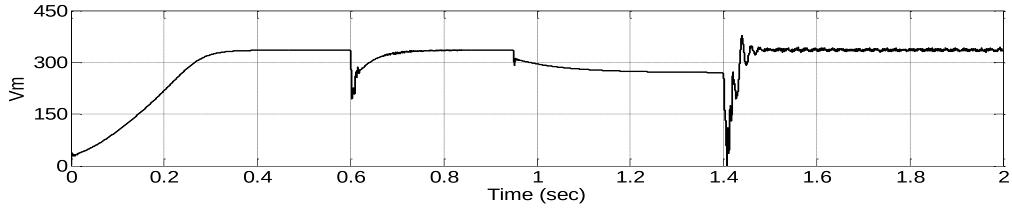
For simulation a 3.7kW, 415V, 7.5A, 4-Pole, 3-phase squirrel cage induction machine is used as generator. Different transient waveforms are illustrated to depict the performance of proposed voltage control scheme supplying balanced/unbalanced linear/non-linear load. The result under various conditions are discussed below.

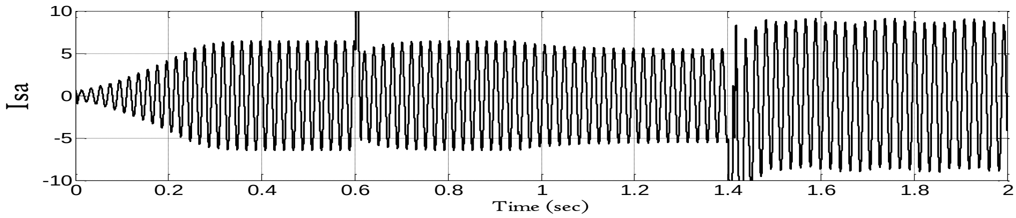
4.5 Result and Discussion

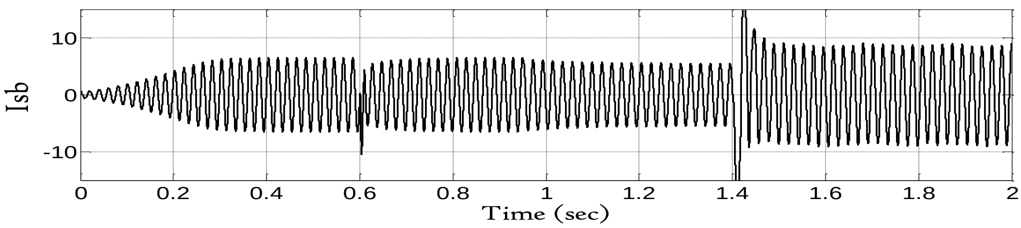
4.5.1 Voltage build-up of SEIG, Connection of Load and Switching of Gate Pulses for R Load

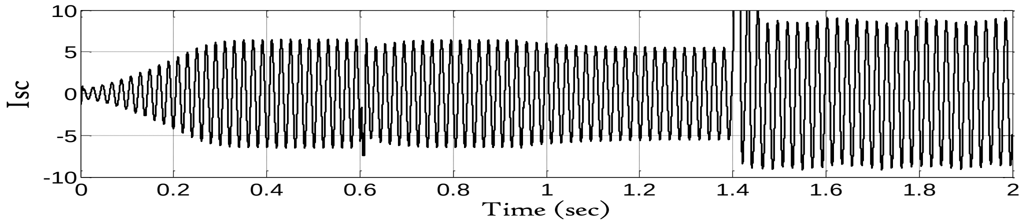
Fig. 4.4 illustrates the performance characteristics of SEIG-STATCOM with fuzzy logic controller feeding a purely resistive load of 1.5 kW. Initially SEIG is at no load and allowed to build-up its terminal voltage through excitation capacitors. Then STATCOM is connected but gate pulses to IGBTs are not given. Then load is switched on which causes the fall in terminal voltage of SEIG. Now the gate pulses are given to switches which restore the SEIG terminal voltage to its rated value.

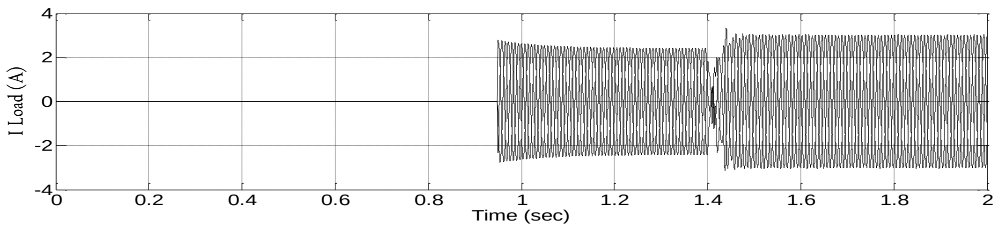

Vabc
Time (sec)

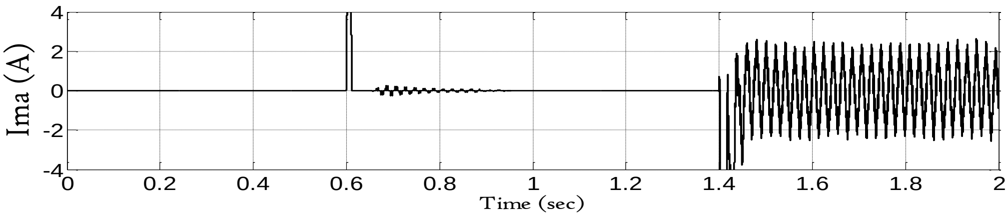

Vm
Time (sec)


Isa
Time (sec)


Isb
Time (sec)


Isc
Time (sec)


I Load (A)
Time (sec)


Ima (A)
Time (sec)

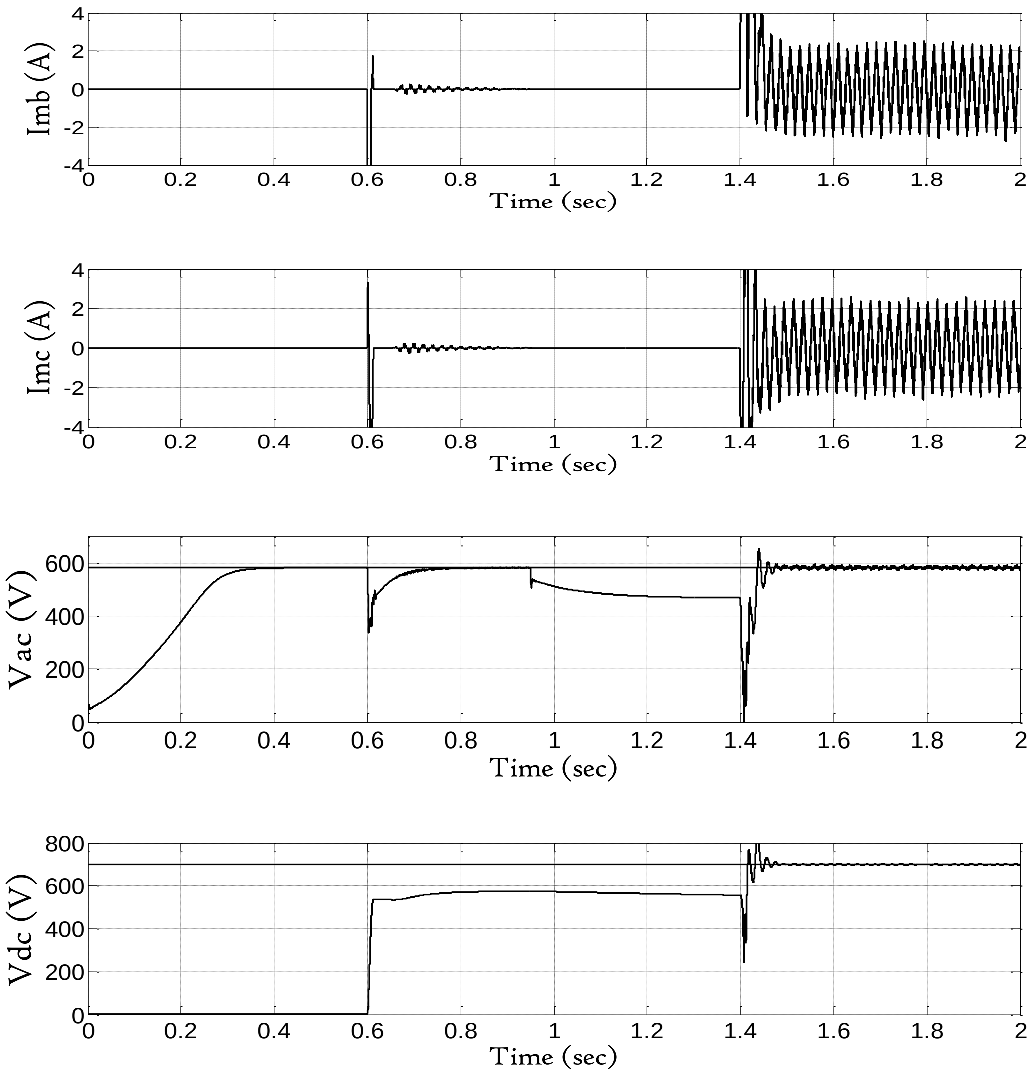


Fig. 4.4 Performance analysis of SEIG-STATCOM with Fuzzy Controller feeding R load of 1.5 kW
(at 0.6 s STATCOM is connected, load is connected at 0.95 s and gate pulses given at 1.4 s)

Response from top to bottom, respectively refers to generator terminal voltage (V_{abc}), peak value of terminal ac phase voltage (V_m), SEIG line currents (I_{sa}, I_{sb}, I_{sc}), three phase ac load current ($I_{Load\ abc}$), three phase STATCOM currents (I_{ma}, I_{mb}, I_{mc}), peak of SEIG terminal voltage (V_p) along with its reference value (V_{pref}) and capacitor voltage (V_{dc}) along with its reference value (V_{dcref}). First voltage is build up and then STATCOM is connected. The dc bus capacitor gets charged to peak of ac line voltage (581 V) through antiparallel diodes. The load is connected at 0.95 s which decreases the SEIG terminal voltage (V_{abc}). At 1.4 s gate pulses are applied to IGBTs of VSI and SEIG voltage returns to its rated value of 335 V (peak phase voltage). The STATCOM supplies the compensating current at 1.4 s which is responsible fulfilling the reactive power requirement of load and regulate the SEIG terminal voltage. The SEIG currents also increases to provide active power requirement of load.

The Steady state waveform of SEIG terminal voltage $(V_{abc})(335\text{ V peak})$, load current $(I_{Load\ abc})$ (3.1 A peak) and SEIG line current $(I_{sa})(9\text{ A peak})$ are depicted in Fig. 4.5 for SEIG-STATCOM system with Fuzzy controller during switching in STACOM feeding resistive load of 1.5 kW.

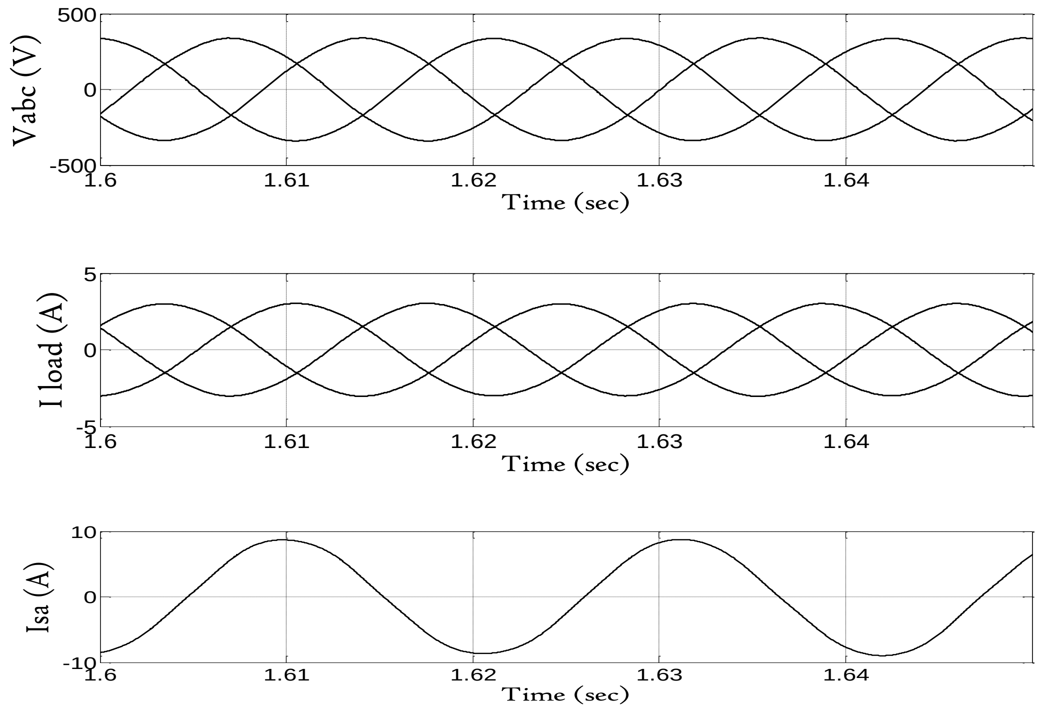
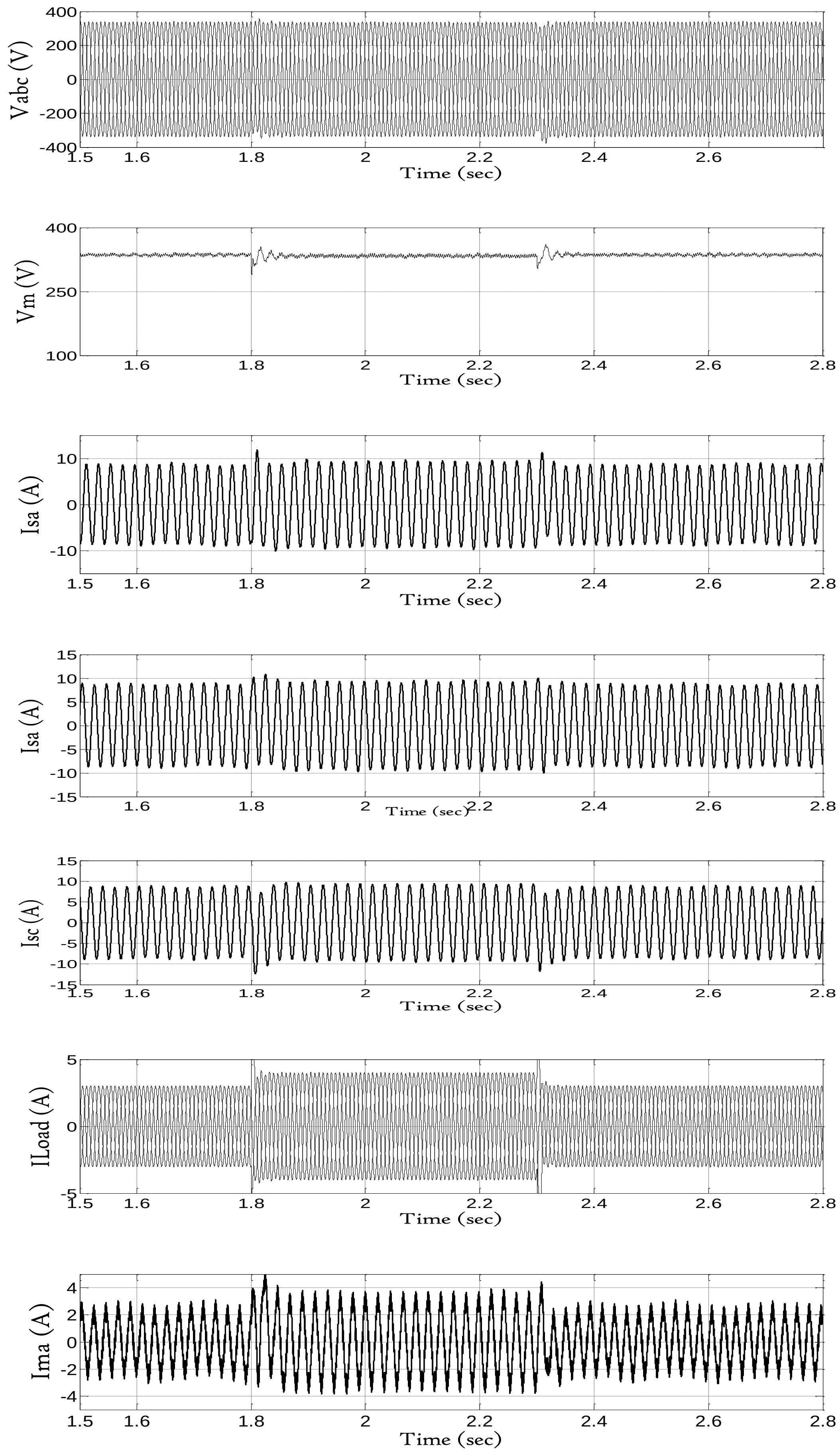


Fig. 4.5 Steady state waveform for SEIG-STATCOM system with Fuzzy controller feeding R load of 1.5 kW

4.5.2 Performance of SEIG-STATCOM with Fuzzy Logic Control feeding R Load

The performance characteristics of generator terminal voltage(V_{abc}), peak value of terminal phase voltage (V_m), generator line currents (I_{sa}, I_{sb}, I_{sc}), three phase load currents $(I_{load\ abc})$, three phase STATCOM current (I_{ma}, I_{mb}, I_{mc}), peak of generator terminal voltage (V_p) along with its reference value and dc capacitor voltage (V_{dc}) along with its reference voltage are illustrated in Fig. 4.6 feeding resistive load with Fuzzy logic controller.


Vabc (V)
Vm (V)
Isa (A)
Isa (A)
Isc (A)
ILoad (A)
Ima (A)
Time (sec)

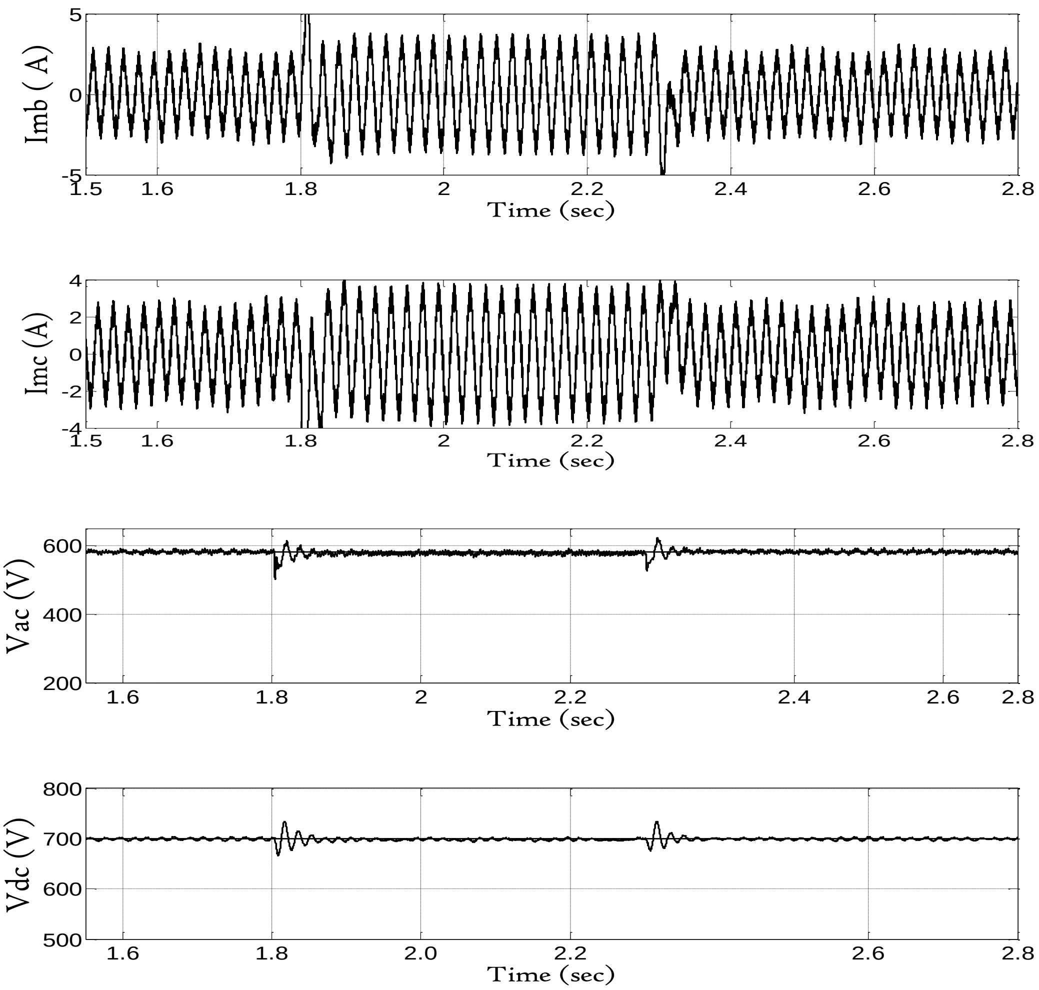


Fig. 4.6 Performance analysis of SEIG-STATCOM system with Fuzzy controller supplying resistive load (Load is changed from 1.5 kW to 2.5 kW at 1.8 s and decrease to 1.5 kW at 2.3 s)

Initially there is 1.5 kW resistive load which changes to 2.5 kW at 1.8 s. With increase in load, load current also changes. Under load change the terminal voltage of generator remains constant with small transient in waveform which dies out quickly. The STATCOM and SEIG current further increases to supply active and reactive power as demanded by load respectively. There is small transient in the dc bus voltage with application of load, but it returns to its reference value within few cycles. At 2.3 s load is again decrease to 1.5 kW. With sudden increase in generated power, the dc bus capacitor absorbs the surplus generated power and thus STATCOM current decreases. The SEIG current also decreases in order to supply active power demand of load. The small transient is present in dc bus voltage with decrease in load which returns to its reference value after few cycles. The ac peak voltage also deviates from its reference value with sudden change in load but it quickly returns to its reference value under Fuzzy logic control.

The Steady state waveform of SEIG terminal voltage $(V_{abc})(335\,\text{V peak})$, load current $(I_{Load\ abc})$ (5 A peak) and SEIG line current $(I_{sa})(10\,\text{A peak})$ are depicted in Fig. 4.7 for SEIG-STATCOM system with Fuzzy controller feeding resistive load of 2.5 kW.

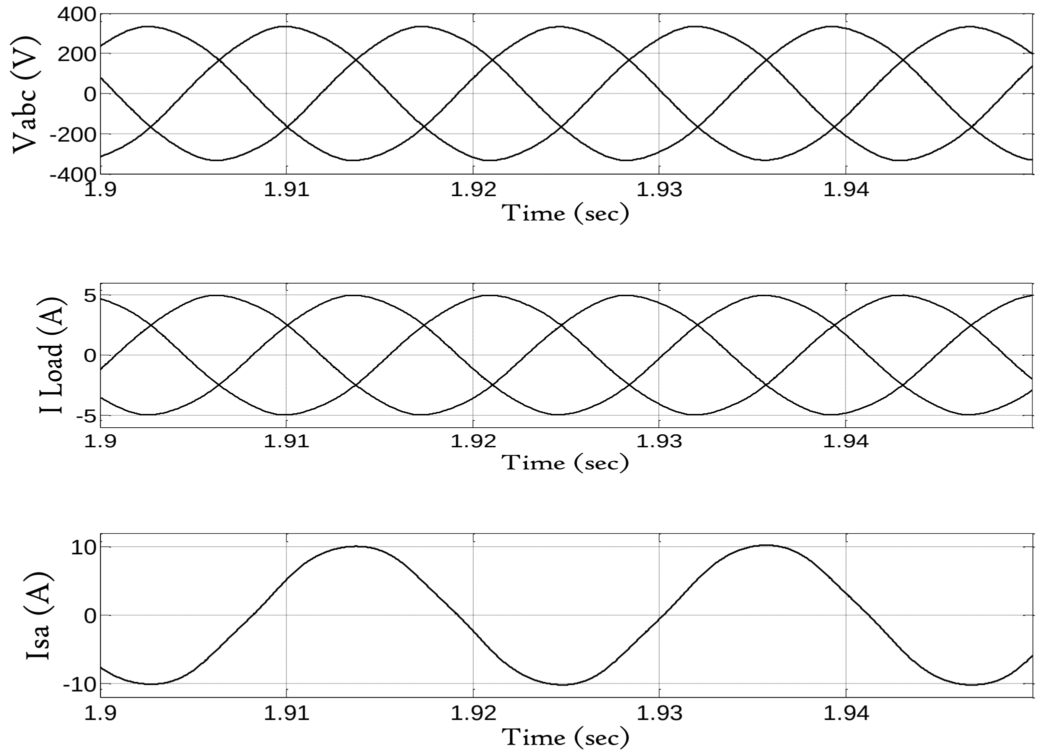
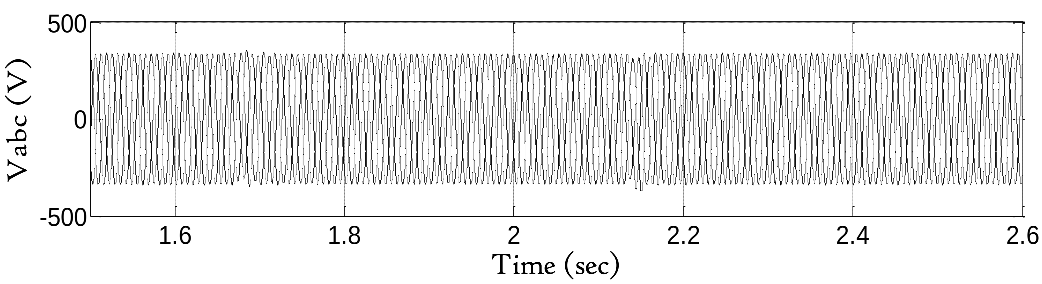
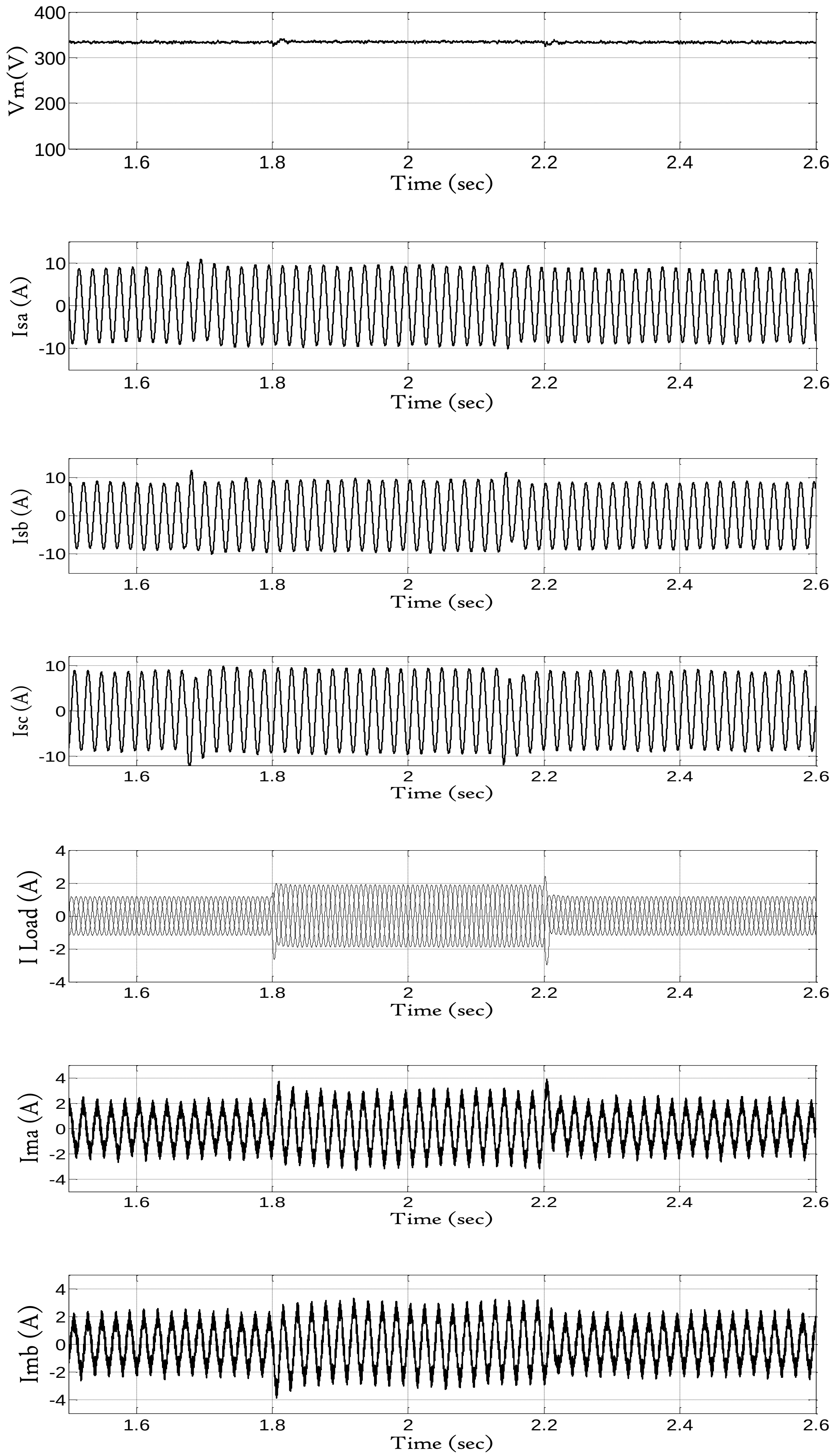


Fig. 4.7 Steady state waveform for SEIG-STATCOM system with Fuzzy controller feeding R load of 2.5 kW

4.5.3 Performance of SEIG-STATCOM with Fuzzy Logic Control feeding R-L Load

The simulated waveforms of SEIG-STATCOM with Fuzzy controller for R-L load at 0.8 pf is depicted in Fig. 4.8. Initially there is a load of 1.5 kW which changes to 2.2 kW.




Vm(V)
Time (sec)
Isa (A)
Time (sec)
Isb (A)
Time (sec)
Isc (A)
Time (sec)
I Load (A)
Time (sec)
Ima (A)
Time (sec)
Imb (A)
Time (sec)

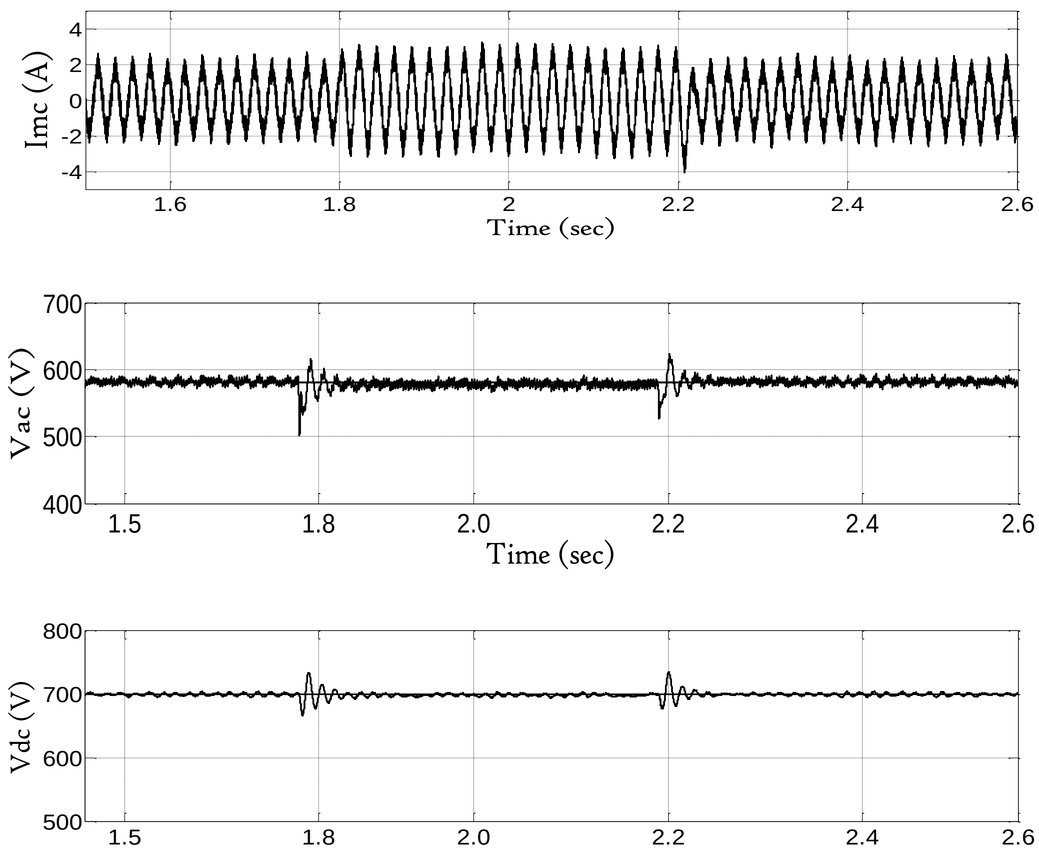


Fig. 4.8 Performance analysis of SEIG-STATCOM with Fuzzy Controller feeding R-L load of 0.8 pf (Load is changed from 1.5 kW to 2.2 kW at 1.8 s and decrease to 1.5 kW at 2.2 s)

Fig. 4.8 shows the transient waveforms of generator terminal voltage(V_{abc}), peak value of terminal phase voltage (V_m), generator line currents (I_{sa}, I_{sb}, I_{sc}), three phase load currents ($I_{load\ abc}$), three phase STATCOM current (I_{ma}, I_{mb}, I_{mc}), peak of ac terminal voltage (V_p) along with its reference value and capacitor voltage (V_{dc}) along with its reference voltage for Fuzzy controller feeding R-L load of 0.8 pf. At 1.8 s load is increased from 1.5 kW to 2.2 kW. Consequently, the generator and STATCOM currents are increases to provide the active and reactive power demand of load. The load current also increases with increase in load. With sudden increase in load an undershoot is observed in capacitor voltage of STATCOM, which supplies necessary reactive power demand of load and generator, to maintaining the SEIG terminal voltage constant. This variation in capacitor voltage settles to its reference value (700 V) after few cycles. At 2.2 s load is again decreased from 2.2 kW to 1.5 kW. The dc bus capacitor absorbed the surplus generated voltage and as a result the STACOM and generator line current decreases but SEIG terminal voltage remains constant at its rated value (335 V). The ac peak voltage also deviates from its reference value with decrease in load but it quickly returns to its reference value due to Fuzzy logic control.

Fig. 4.9 illustrates the steady-state waveforms of SEIG –STATCOM system depicting SEIG terminal voltage(V_{abc})(335 V peak), SEIG line current (I_{sa})(7.1 A peak) and load current waveform ($I_{Load\ abc}$) (1.5 A peak) feeding 0.8 pf R-L load of 1.5 kW

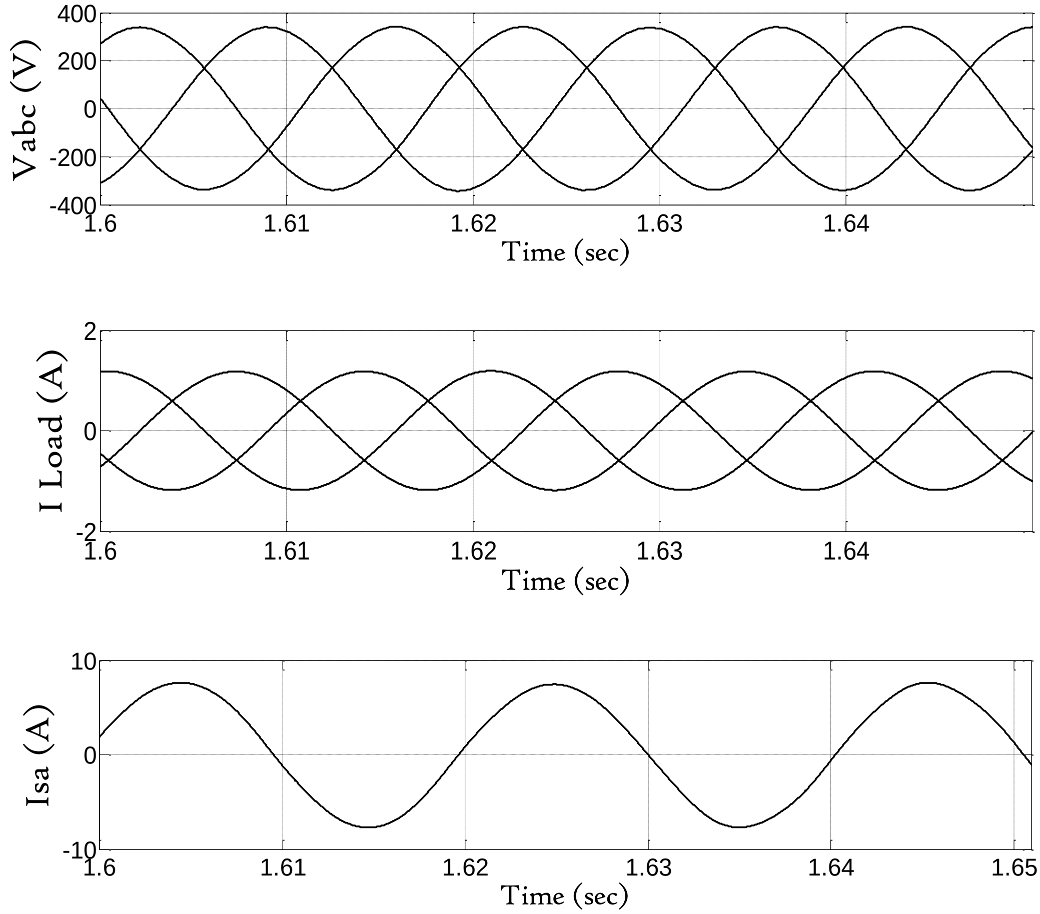
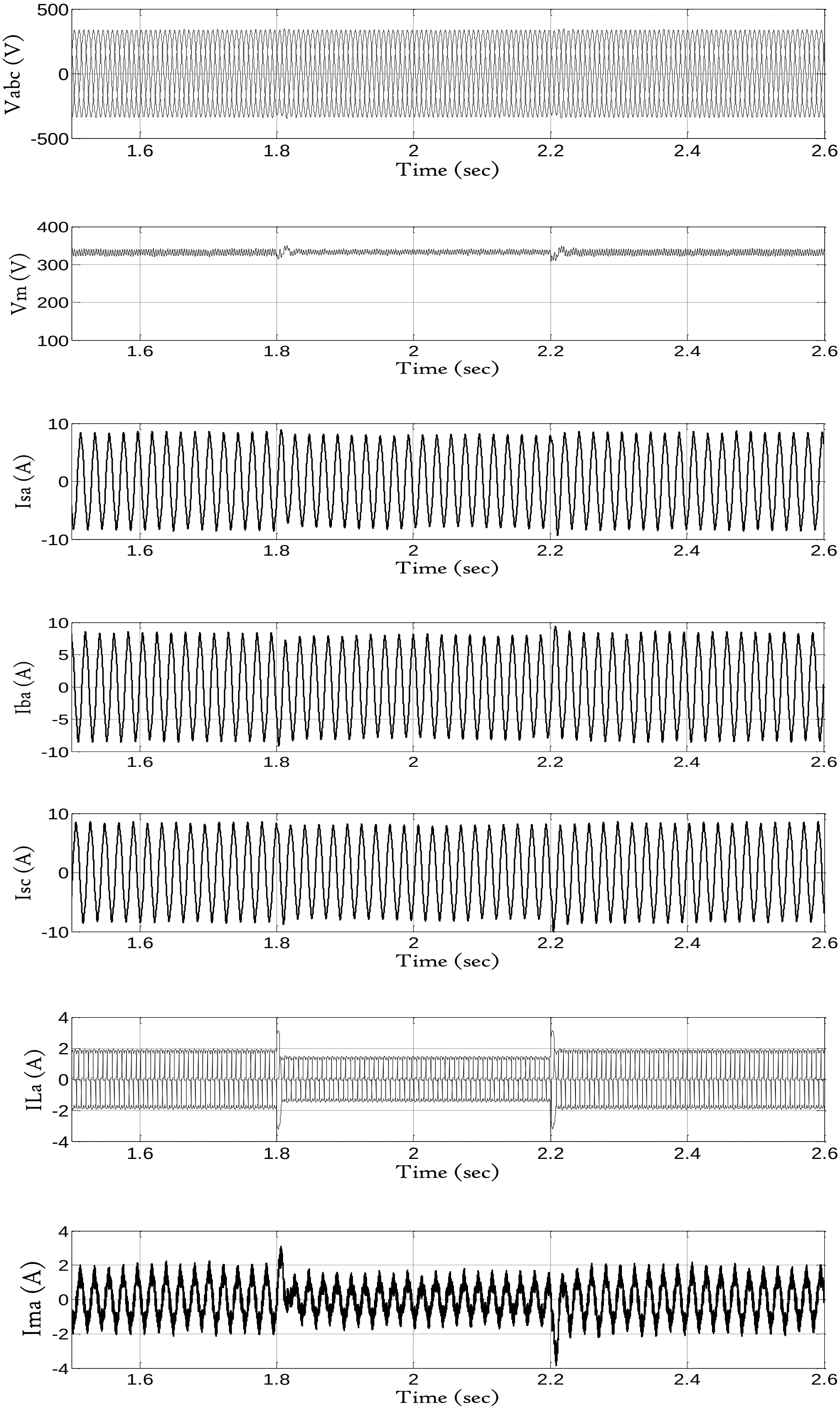


Fig. 4.9 Steady state waveforms of SEIG-STATCOM with Fuzzy Controller feeding 0.8 pf R-L load of 1.5 kW

4.5.4 Performance of SEIG-STATCOM with Fuzzy Logic Control feeding Non-linear load (Three Phase Diode Rectifier with Resistive load)

The simulated waveforms of generator terminal voltage (V_{abc}), peak value of terminal phase voltage (V_m), generator line currents (I_{sa}, I_{sb}, I_{sc}), three phase load currents ($I_{load\ abc}$), three phase STATCOM current (I_{ma}, I_{mb}, I_{mc}), peak of ac terminal voltage (V_p) and capacitor voltage (V_{dc}) for SEIG-STATCOM system with Fuzzy logic control feeding three phase diode rectifier with resistive load is shown in Fig. 4.10


Vabc (V)
Time (sec)
Vm (V)
Time (sec)
Isa (A)
Time (sec)
Iba (A)
Isc (A)
Time (sec)
ILa (A)
Time (sec)
Ima (A)
Time (sec)

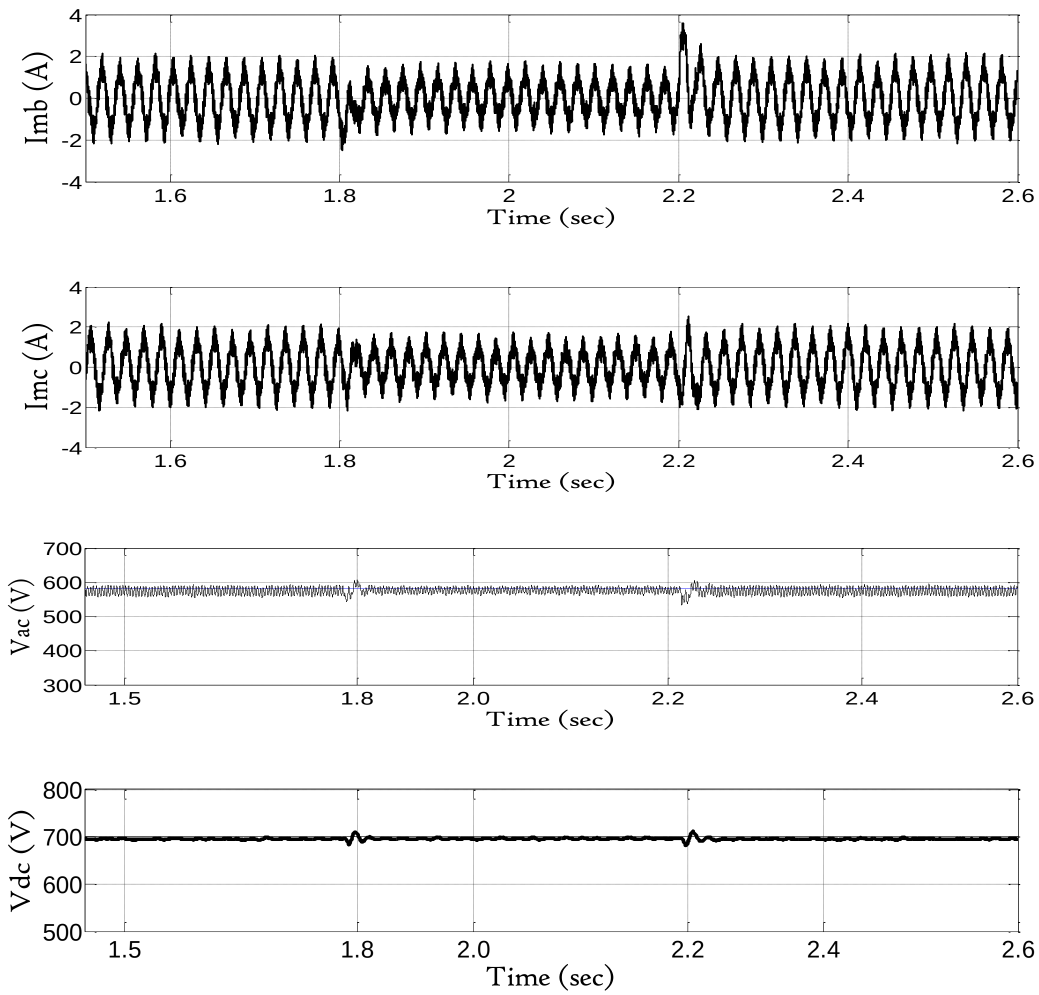


Fig. 4.10 Performance characteristics of SEIG-STATCOM system with Fuzzy controller feeding diode rectifier with R load is decrease from 2 kW to 1.5 kW at 1.8 s and increase from 1.5 kW to 2 kW at 2.2 s

Response from top to bottom, respectively refers to generator voltage (V_{abc}), peak value of terminal phase voltage (V_m), SEIG line currents (I_{sa}, I_{sb}, I_{sc}), three phase ac load current ($I_{Load\ abc}$), three phase STATCOM currents (I_{ma}, I_{mb}, I_{mc}), peak value of SEIG terminal voltage (V_p) along with its reference value (V_{pref}) and capacitor voltage (V_{dc}) along with its reference value (V_{dcref}) for SEIG-STATCOM system feeding a non-linear load. At 1.8 s the resistive load on three phase rectifier is decrease from 2 kW to 1.5 kW. With decrease in the load the terminal voltage of generator remains constant but load current decreases. The dc bus capacitor absorbs the surplus generated power as a result of which a overshoot is observed in capacitor voltage, which tracks down to its reference voltage with in few cycles due to Fuzzy control action. At 2.2 the resistive load on three phase diode rectifier is further increased from 1.5 kW to 2 kW. With increase in load, the STACOM, generator and load current also increases to provide the necessary active and reactive powers to load. Due to increase in load an undershoot is observed in capacitor voltage which returns to its reference value within few cycles under Fuzzy control action.

The Steady state waveform of SEIG terminal voltage ($V_{abc} - 335\text{ V peak}$), load current ($I_{Load\ abc}$-2 A peak) and SEIG line current ($I_{sa} - 9\text{ A peak}$) are depicted in Fig. 4.11 for SEIG-STATCOM system feeding non-linear load.

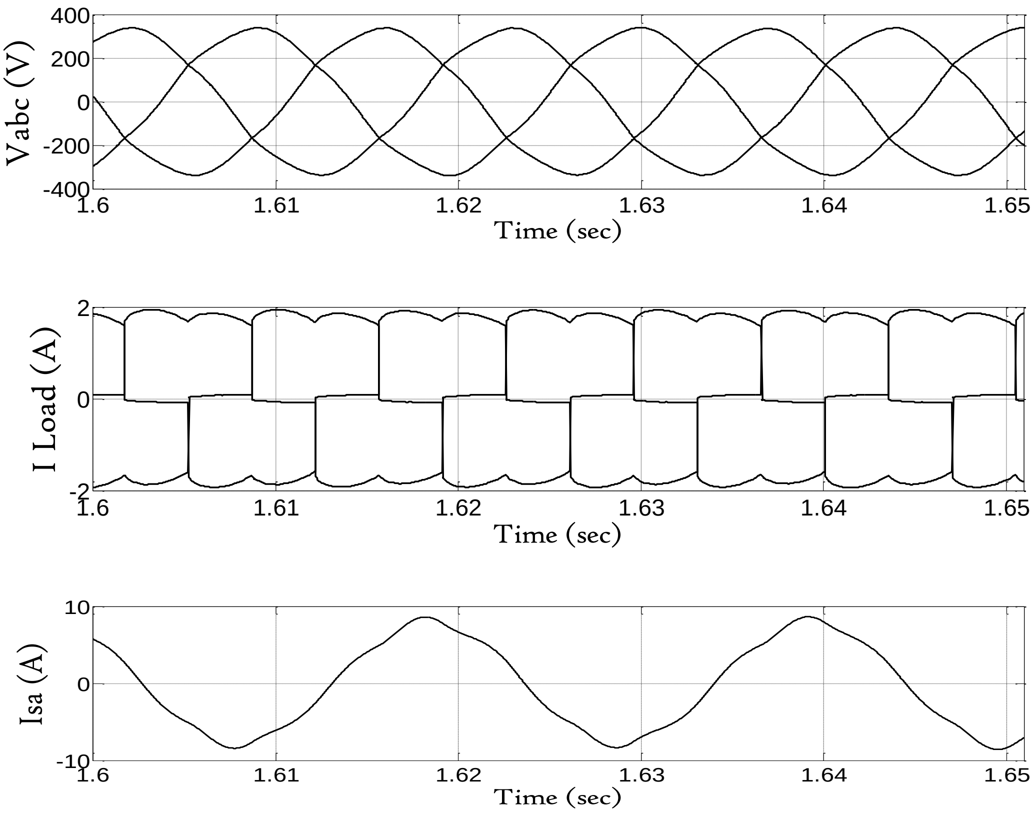


Fig. 4.11 Steady state waveforms of SEIG-STATCOM with Fuzzy Controller feeding three phase diode rectifier with resistive load of 2 kW

Fig. 4.12 depicts the response of dc bus capacitor voltage of conventional PI controller and Fuzzy controller. From the response it is observed that the performance of PI controller and Fuzzy controller are quite satisfactory. But fuzzy logic controller attain steady state value in nearly 0.3 s whereas PI controller attains steady state value after 0.8 s. the peak overshoot in dc voltage is 890 V in case of PI control while in Fuzzy control, it is 785 V. The settling time of Fuzzy logic controller is less than conventional PI control and steady state response of Fuzzy controller is much smoother as compared to PI control i.e. fuzzy control nearly maintains the steady state value as constant as possible.

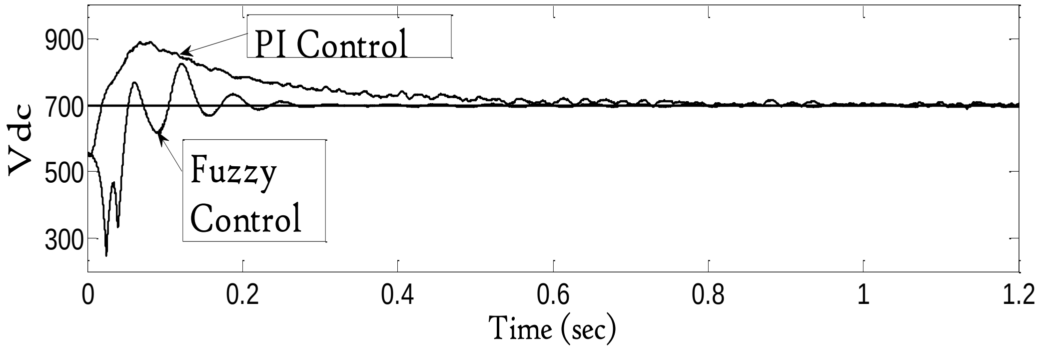


Fig. 4.12 DC bus capacitor voltage during switch on response

4.6 Conclusion

The modelling and simulation of SEIG-STATCOM system using Fuzzy controller has been carried out for both linear and non-linear loads. From the simulation results, it is clear that Fuzzy controller gives better performance than PI controller under various load conditions. The Fuzzy controller has less settling time, fast dynamic response and small peak overshoot as compared to conventional PI control. Thus the implementation of Fuzzy controller instead of PI controller is more beneficial and easy to use.

Chapter-5

MAIN CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 Main Conclusion

The research work presented in the thesis mainly deals with analysis and development of fuzzy and PI voltage controller for self-excited induction generator based on STATCOM. The modelling and simulation of SEIG-STATCOM has been carried out for different types of loads. The MATLAB based model of SEIG is developed in q and d stationary reference frame. The SEIG develops its terminal voltage with the help of excitations capacitors. But with application of load, terminal voltage falls down from its rated value. A STACOM based voltage regulator is developed for regulating the SEIG voltage in MATLAB. The proposed scheme for maintaining the voltage of SEIG constant is simple and easy to implement. The STATCOM improves the voltage regulation by injection of compensation currents. The STATOM is design for various loads like linear/ non-linear, balanced/unbalanced. From the simulation result it has been found that the non-linear load injects harmonics in the system, which are also eliminated by STATCOM. Hence it is concluded that STATCOM can act as voltage regulator, load balancer and harmonic eliminator. In designing of STATCOM, PI and Fuzzy controllers are used and their simulation result are compared. The Fuzzy controller based STATCOM gives better dynamic performance. From the simulation result it is also found that the Fuzzy controller has less peak overshoot, fast response and smooth steady state response as compared to conventional PI control. Hence SEIG-STATCOM with fuzzy controller is a good candidate for improving the performance of the regulator.

5.2 Scope for future work

The voltage regulation of self-excited induction generator using STATCOM have been investigated for various loads (linear/non-linear) with PI and Fuzzy controller for improving the performance of SEIG in standalone application. However further research work can be carried out for better operation of SEIG. The areas in which further work can be done are as follows

1) The SEIG-STATCOM system can be developed for dynamic load also which increases the flexibility of controller as it can be used for any type of load either linear or non-linear, static or dynamic, balanced or unbalanced.
2) The STATCOM based controller can be developed for three phase SEIG feeding single phase load using Fuzzy logic controller because fuzzy controller gives better dynamic response as compared to PI controller.
3) Voltage regulation for SEIG driven by variable speed prime movers using STACOM can be developed.
4) In standalone application using wind energy conversion system, the performance of STATCOM based controller may be investigated using maximum power point tracking.

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